Contract NAS 8-11450

MSFC/NASA

Huntsville, Alabama

THE TRAVELERS RESEARCH CENTER, INC.

250 CONSTITUTION PLAZA / HARTFORD, CONNECTICUT

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PRELIMINARY ESTIMATES OF ENVIRONMENTAL EXPOSURE FOR FUEL AND EXHAUST PRODUCTS—

Volume I
Part I Methods and Preliminary Estimates for MSFC
Part 2 Recommended Experimental Design for MSFC

Keith D. Hage
Norman E. Bowne

Principal Investigator
Glenn R. Hilst

January 1965
7225-153

Prepared for

Aerospace Environment Office
Aero-Astro Dynamic Laboratory
Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama

under Contract NAS 8-11450

by

THE TRAVELERS RESEARCH CENTER, INC.

250 Constitution Plaza Hartford, Connecticut 06103

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PART 1 - MODEL DEVELOPMENT

1.0 Statement of the Problem

Test and launch operations with rocket propulsion engines are accompanied inevitably by the release of fuel vapors and combustion products into the surrounding environment. Furthermore, although fuel transport, transfer, and storage procedures can be designed in such a way that routine escape of liquids or vapors will not occur, a risk of inadvertent release exists with each operation. Since under normal operating conditions rapid dilution takes place in the atmosphere such operations do not constitute a serious pollution problem at typical sites. Recently, however, fuels with relatively high toxicity levels have been proposed for operational use, and this has led to a requirement for estimates of gas and vapor concentrations and exposure times both in the immediate vicinity of the operational site and at distances of up to several miles from the site. Some of the meteorological aspects of the safety problem are examined in detail in this report for two NASA sites, the Marshall Space Flight Center (MSFC) at Huntsville, Alabama, and the Kennedy Space Center (KSC) at Cape Kennedy, Florida.

The initial production and subsequent growth of gaseous clouds from rocket exhaust or conflagration sources and of vapor clouds from cold liquid spills are complex phenomena involving many physical processes. Only by simplification of the details of these processes is it possible to attempt to model the behavior of the clouds.

Broadly speaking, the initial moments of cloud formation may be characterized as a period of rapid transition from release conditions to quasi-ambient conditions of pressure, temperature, and density. During this interval, in launch and test releases, energy losses take place by radiative cooling, conduction, and frictional dissipation accompanying sonic and shock pressure waves. In the case of a liquid fuel spill rapid vaporization with or without partial combustion may occur as the pressurized liquid adjusts to ambient conditions of temperature and pressure. Because of intense mixing with the atmosphere, at times of the order of tens of seconds to a few minutes following release, the clouds tend to assume symmetrical shapes that can be described roughly as a convex meniscus (cold spill over an area), a curved teardrop plume (static test), an inverted teardrop (normal launch), or a sphere or toroid with stem (fire on pad). The initial cloud from an abort action in flight cannot be described in such a simple fashion. However, a source of this nature, as well as the upper portions of a normal launch exhaust plume, involving the vehicle trajectory, would be expected to contribute (to nearby ground-level concentrations) much less significantly than the other source configurations.

For MSFC at Huntsville releases of toxic products in inadvertent cold liquid spills and in static firing tests are of greatest concern. In the latter, mechanical deflection and buoyant ascent of the material produce an elevated volume source that should lead to surface concentration patterns quite different from those to be expected from the ground release represented by a cold spill. For KSC at Cape Kennedy, estimates of potential hazards due to normal launch exhaust and conflagrations are required in addition to those from cold liquid spills due to pipeline leakages.

1.1 Preliminary Models

1.1.1 Introduction

In an effort to derive quantitative estimates of surface concentrations, a simple mathematical model of cloud formation and growth was formulated and solved for selected initial and boundary conditions. The model represents a preliminary attempt to identify and simulate the essential physical processes. In view of the fragmentary nature of present theoretical understanding of, for example, entrainment and eddy diffusion processes, this approach to the problem can be meaningful only if it is followed by experimental testing and model refinement as dictated both by the results of tests and by improved understanding of the growth processes.

The transport and spread of the gas or vapor cloud was divided into two phases. In the first phase it was assumed that the cloud growth and ascent were controlled by gross entrainment of environmental air (heated source) or by vaporization without ascent (cold source). The concentration distribution and spatial dimensions of the cloud under quasi-ambient conditions of pressure and temperature were then used as the initial conditions for the second phase in which further cloud growth was assumed to be controlled by eddy diffusion with and without deposition at the lower boundary.

1.1.2 Phase 1

1.1.2.1 Buoyant Rise of Heated Clouds

Although no exact theory exists for the ascent of a heated puff or plume in the atmosphere, several semi-empirical equations for stabilization height have been reported in the literature. In 1950 Machta [12] described a model in which the initial excess cloud temperatures were reduced to ambient values by adiabatic cooling and by entrainment mixing. Defining the maximum height H_1 as the level of zero excess cloud temperature and assuming constant values of ambient vertical potential temperature gradient $\partial\Theta/\partial z$ and entrainment rate $\epsilon = M^{-1}\,\partial M/\partial z$, Machta found

$$H_1 = \frac{1}{\epsilon} \ln \left\{ \frac{\epsilon}{\partial\Theta/\partial z} \left[(\Delta\Theta)_0 + \frac{\partial\Theta/\partial z}{\epsilon} \right] \right\} \qquad (1\text{-}1)$$

where $(\Delta\Theta)_0$ is the difference in potential temperature between cloud and environment at height $z = 0$. By dividing the atmosphere into layers, allowances can be made in the model for variable values of $\partial\Theta/\partial z$ and ϵ. According to Eq. (1-1) the maximum height H_1 is much more sensitive to the entrainment rate than to the strength of the heat source. A value of $0.5 \times 10^{-5}\ \mathrm{cm}^{-1}$, based on observations of cumulus cloud growth was used by Machta for the entrainment constant.

Sutton [20] assumed that the spread of heat in a rising volume was analogous to the spread of matter in a diffusing puff carried horizontally by the wind. Using mixing-length theory to describe the entrainment of ambient air into the buoyant volume and solving for the level H_2 of zero excess potential temperature Sutton found

$$H_2 = \left[\frac{2(3m + 2p)Q_H}{9c_p \rho \pi^{3/2} C^3 ap}\right]^{1/(p + 3m/2)} \tag{1-2}$$

where c_p is the specific heat of air at constant pressure, ρ is air density, Q_H is the strength of the heat source, C is Sutton's generalized diffusion coefficient, m is a parameter ($1 \leq m \leq 2$) expressing the intensity of mixing, and a and p are obtained from a power law $\Theta(0) + az^p$ fitted to the ambient potential temperature profile. For a constant vertical potential temperature gradient ($p = 1$), and $m = 7/4$, the exponent of Q is approximately 0.276 showing again the relative insensitivity of cloud height to the strength of the heat source.

Morton, Taylor, and Turner [13] assumed (a) that the rate of entrainment at the cloud edge was proportional to a characteristic vertical velocity within the rising cloud at the same height, (b) that horizontal profiles of mean vertical velocity and mean buoyancy force were similar at all heights, and (c) that local density variations were small compared to the ambient fluid density. These assumptions, and application of the principles of conservation of energy, mass, and momentum, led to the following solution for height of rise, H_3, in an atmosphere of uniform stability

$$H_3 = \frac{1}{4}\left(\frac{3}{\pi}\right)^{1/4} (\alpha k)^{-3/4} \left(\frac{gQ_H}{T_1 \rho_1 c_p}\right)^{1/4} \left[\frac{g\Gamma}{T_1}(1 + n)\right]^{-1/4} X_1, \tag{1-3}$$

where g is the acceleration of gravity, T_1 and ρ_1 are ambient values of air temperature and density, respectively, at source level, Γ is the adiabatic lapse rate of temperature, and n is the ratio of actual (uniform) lapse rate to Γ. The constant k represents the ratio of mean vertical velocity to maximum vertical velocity at any height and the product (αk), when multiplied by the vertical velocity at the center of the cloud at height z represents the entrainment rate at that height. The value of the product (αk) was determined by Morton, et al [13] to be 0.285 from the slope of a regression line relating the two sides of Eq. (1-3) on the basis of $X_1 = 4.2$ and laboratory measurements of all other parameters. The behavior of the solution in this model, as in that of Priestley and Ball [16], is such that the cloud overshoots the height at which buoyancy forces first vanish, then oscillates about a level somewhat higher than this. According to the solution curves the nondimensional parameter X_1 assumes the value 4.2 at the final stabilization height. With $X_1 = 4.2$ and $(\alpha k) = 0.285$, Eq. (1-3) reduces to

$$H_3 = 2.64 \left(\frac{Q_H}{\rho_1 c_p} \right)^{1/4} \left[\Gamma (1 + n) \right]^{-1/4} \qquad (1\text{-}4)$$

Once again cloud height was found to be relatively insensitive to the strength of the heat source.

For a maintained plume from a continuous source emitting heat at rate Q_H, Morton, Taylor, and Turner found

$$H_3 = 0.410\, \alpha^{-1/2} \left(\frac{g Q_H}{T_1 \rho_1 c_p} \right)^{1/4} \left[\frac{g\Gamma}{T_1} (1 + n) \right]^{-3/8} x_1 \qquad (1\text{-}5)$$

where α is a proportionality constant that provides a measure of the rate of entrainment ($\alpha = .093$ from laboratory measurements) and where $x_1 = 2.8$ at the level for which the vertical velocity first vanishes.

For a number of reasons none of these models can be expected to provide precise values of H in the present problem. In the first place, assumption (c) on page 4, common to all models, is violated in the early moments of cloud formation both because of high temperatures and because of the presence of local volumes of unmixed gas with densities appreciably different from that of air even at ambient temperatures and pressures. For this reason, the initial rise of hot gases may resemble more closely the rise of a bubble in water in which turbulent entrainment is not a dominant process. Secondly, at heights above that for which buoyancy forces first vanish, there are uncertainties regarding the choice of final stabilization height, and it is unlikely that these uncertainties can be resolved without a more detailed consideration of compensating downward motions. Finally, all models involve, and are rather sensitive to, an entrainment rate that must be determined empirically. Some uncertainty exists as to the appropriateness of the few existing measurements of this quantity in the present problem.

A more serious limitation of the models results from their restriction to a calm atmosphere. A substantial reduction in stabilization height can be expected in the presence of a strong wind since mixing and entrainment will occur along the horizontal component as well as the vertical component of the cloud trajectory. Two equations, based entirely on observations of the heights of rise of hot gases in the atmosphere in the presence of a mean wind speed $\overline{U}$ have been derived by Thomas [21].[1]

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[1] Observed cloud heights resulting from the combustion of small quantities of fuel have been summarized by [6] in a paper received too late for consideration in this study.

In their original form, these equations are

$$\text{Instantaneous Source:} \quad H_4 = 100 \left[\frac{100\,W}{\overline{U}\,(\Delta T + 1/4)} \right]^{1/3} \tag{1-6}$$

$$\text{Continuous Source:} \quad H_4 = \frac{5000 Q_H^{1/4}}{\overline{U}} \tag{1-7}$$

where H_4 is the maximum height of rise (ft), $\overline{U}$ is the mean wind between the source and H_4 (ft sec^{-1}), ΔT is the temperature difference (°F) between the source and H_4, W is source strength in pounds of explosive, and Q_H is source strength in megawatts. Converting units, assuming for W in Eq. (1-6) a conversion factor of 1.64×10^6 calories per pound corresponding to the heat of combustion of TNT, these equations can be written

$$\text{Instantaneous Source:} \quad H_4 = .375 \left[\frac{Q_H}{\overline{U}\,(\Delta T + 1/4)} \right]^{1/3} \tag{1-8}$$

$$\text{Continuous Source:} \quad H_4 = \frac{21\, Q_H^{1/4}}{\overline{U}} \tag{1-9}$$

where H_4 is height in meters, $\overline{U}$ is mean wind speed in m sec^{-1}, ΔT is temperature difference (°F), and Q_H is source strength (cal. in Eq. [1.8] and cal. sec^{-1} in Eq. [1.9]). Both equations must be solved by cut-and-try methods since the final height H_4 is involved implicitly in the evaluation of $\overline{U}$ and ΔT. Furthermore, both equations are clearly invalid for small values of $\overline{U}$.

For purposes of comparison, values of H_2 (Eq. 1-2), H_3 (Eq. 1-4), and H_4 (Eq. 1-8) for the maximum height of rise of a cloud from an instantaneous hot source were calculated for selected values of Q_H. The results are given in Table 1.1.

The source strengths Q_H in Table 1.1 are typical of those of interest in the present problem. A standard atmosphere vertical temperature gradient of -6.5°C km^{-1} was used in each equation. Machta's formula (Eq. 1-1) was not

TABLE 1-1
MAXIMUM HEIGHT OF RISE H(m) FOR
SELECTED SOURCE STRENGTHS Q_H (cal.)

Source strength Q_H (cal.)	Maximum Height of Rise H			
	H_2 (Eq. 1-2)	H_3 (Eq. 1-4)	H_4 (Eq. 1-8) (m)	
			$\overline{U}$ = 2m sec^{-1}	$\overline{U}$ = 6 m sec^{-1}
10^9	540	480	210	170
10^{10}	1000	850	380	300
10^{11}	1910	1500	690	530
10^{12}	3550	2680	1240	960

evaluated due to lack of information on entrainment rates appropriate to low-yield fires and explosions. According to Table 1.1 the maximum heights given by the Morton, Taylor, and Turner formula (Eq. 1-4) were systematically lower than those derived from Sutton's model (Eq. 1-2). Mean wind speeds of 2 to 6 m sec^{-1} resulted in a further reduction in maximum height by a factor of 0.3 to 0.5 according to Thomas (Eq. 1-8). Since it is questionable whether or not typical values of Sutton's generalized diffusion coefficient (C in Eq. 1-2) are valid for clouds that move relative to the air [7, p. 82] only the formulae of Morton, et al, and Thomas were used in this study.

1.1.2.2 Cloud Dimensions at Stabilization Height

It was assumed that gas concentrations and excess heat in the rising cloud were distributed as a trivariate normal function in space. In such a distribution 99.3 percent of the total mass (and excess heat) is contained within a sphere of radius 4σ where σ is the standard deviation along any radius. The distribution function for concentration χ is

$$\chi = \frac{Q_m}{2\pi^{3/2}\sigma^3} \exp - \frac{r^2}{2\sigma^2} \tag{1-10}$$

where Q_m is the total mass of gas in the cloud and r is radial distance from the (rising) center of the cloud. For lack of suitable alternative procedures, Sutton's [20] analogy between the growth of a rising hot cloud and the growth of a smoke puff carried horizontally in the wind was used to evaluate σ. On this basis

$$\sigma 2 = \frac{C^2 Z^m}{2} \tag{1-11}$$

where C is Sutton's generalized diffusion coefficient and m is a mixing parameter. The use of Eq. (1-11) for this purpose is questionable since it is not clear that the values of C and m established for growth of advected clouds are valid for clouds that possess systematic motion relative to the air.

If the gas cloud has a finite volume characterized by variance σ_0^2 at $Z = 0$, the concept of a virtual source can be introduced giving

$$\sigma 2 = \frac{C^2 (Z + Z_0)^m}{2} \tag{1-12}$$

where Z_0 is the distance from the virtual source ($\sigma = 0$, $Z = Z_0$) to the height at which buoyant ascent is initiated ($\sigma = \sigma_0$, $Z = 0$).

1.1.2.3 Cloud Ascent Due to Mechanical Deflection

The initial ascent of exhaust gases from static firing tests is controlled to a large extent by the momentum of the exhaust and the deflector angle. Motion pictures of actual tests carried out at MSFC were used to obtain rough estimates of the altitudes to which the exhaust jet ascended before measurable differences could be detected between the cloud trajectory angle and the deflector angle for various release durations and rates. These altitudes were then used as the starting point for computations of buoyant ascent.

1.1.2.4 Vaporization

For modelling purposes it was assumed that liquid fuel from spills and leakages would be transformed instantaneously into a hemispheric vapor cloud covering a small area of the earth's surface. The dimensions of the vapor cloud were determined from a trivariate normal distribution allowing for a transition from initial conditions of density, pressure, and temperature to ambient conditions according to the Gas Law. For combinations of combustion and vaporization the heat generated by combustion was distributed over the entire volume of vapor and gas and buoyant ascent was computed as described in Section 1.1.2.1.

1.1.3 Phase 2

1.1.3.1 Introduction

The trivariate normal distribution function in a form suitable for an elevated instantaneous volume source was selected as the basic framework for modelling the eddy diffusion of mass subsequent to stabilization of the initial cloud. In this model the concentration χ at time t and at a point x, y, z in a Cartesian coordinate system is given by

$$\chi(x, y, z, t) = \frac{Q_m}{(2\pi)^{3/2}\,\sigma_x(x')\,\sigma_y(x')\,\sigma_z(x')} \times \tag{1-13}$$

$$\left[\exp - \frac{1}{2}\left\{\frac{(x-\xi)^2}{\sigma_x^2(x')} + \frac{(y-\eta)^2}{\sigma_y^2(x')}\right\}\right]\left[\exp - \frac{1}{2}\left\{\frac{(z-\zeta)^2}{\sigma_z^2(x')}\right\} + \exp - \frac{1}{2}\left\{\frac{(z+\zeta)^2}{\sigma_z^2(x')}\right\}\right]$$

where Q_m is the total mass of material released at the source; σ_x, σ_y, and σ_z are the standard deviations of the distribution along the three coordinate axes at distance ξ from the source; ξ, η and ζ are the coordinates of the (moving) cloud center; $x' = x_0 + \xi$ where x_0 is the distance from the virtual source to the true source located at the origin of the axis; and the coordinate system is chosen so that the x-axis is parallel to the wind direction at source height, the y-axis is horizontal and normal to the x-axis, and the z-axis is vertical. Since in all applications of the model the values of the standard deviations σ_x, σ_y, and σ_z were specified from field measurements, Eq. (1-13) is entirely descriptive with no specification of the physical mechanisms by which such a distribution is achieved. The justification for its use rests primarily on the evidence provided by concentration profile measurements in the atmosphere near a point source (8,p.132). While the concentration patterns from individual tests with instantaneous point sources often show marked departures from the Gaussian form ensembles of such results, under apparently similar gross meteorological conditions, show little evidence of systematic non-Gaussian form. Conversely, in applying the model to real, quasi-instantaneous sources it must be kept in mind that large deviations from the predicted concentration pattern are to be expected in individual realizations, particularly at small times and distances.

In the initial model it was assumed that the altitude of the cloud center was invariant in space and time and that the direction and speed of the wind were constant in time and horizontal space. Thus

$$\left.\begin{aligned} \zeta &= H \\ \eta &= 0 \\ \xi &= \overline{U}_h t \end{aligned}\right\} \qquad (1\text{-}14)$$

Since $\xi \rightarrow 0$ as $t \rightarrow 0$ the distribution of χ at $t = 0$ has the form of two trivariate normal distributions with variances $\sigma_x^2(x_0)$, $\sigma_y^2(x_0)$, and $\sigma_z^2(x_0)$ and with origins at $x = 0$, $y = 0$, $z = \pm H$. As $t \rightarrow \infty$, $\chi \rightarrow 0$; and as $x \rightarrow \infty$, $y \rightarrow \infty$, $z \rightarrow \infty$; $\chi \rightarrow 0$. The mass continuity condition expressed by

$$\int_{-\infty}^{\infty} \int^{\infty} \int_0^{\infty} \chi \, dx dy dz = Q_m \qquad (1\text{-}15)$$

is also satisfied by Eq. (1-13).

Introducing Eq. (1-14) into Eq. (1-13) and solving for ground-level concentration

$$\chi(x,y,z,t) = \frac{2Q_m}{(2\pi)^{3/2}\sigma_x(x')\sigma_y(x')\sigma_z(x')} \exp - \frac{1}{2}\left\{\frac{(x - U_h t)^2}{\sigma_x^2(x')} + \frac{y^2}{\sigma_y^2(x')} + \frac{H^2}{\sigma_z^2(x')}\right\} \tag{1-16}$$

Dosage values D were obtained by integration of Eq. (1-16) over time at a fixed point. Assuming slow variations in σ_x^2, σ_y^2, and σ_z^2

$$D(x,y,z) = \int_0^\infty \chi\, dt \approx \frac{2Q_m}{(2\pi)^{3/2}\sigma_x(x')\sigma_y(x')\sigma_z(x')} \exp - \frac{1}{2}\left\{\frac{y^2}{\sigma_y^2(x')} + \frac{H^2}{\sigma_z^2(x')}\right\} \int_0^\infty \exp - \frac{1}{2}\left\{\frac{(x - U_h t)^2}{\sigma_x^2(x')}\right\} dt$$

$$= \frac{Q_m}{2\pi\sigma_y(x')\sigma_z(x')U_h} \exp - \frac{1}{2}\left\{\frac{y^2}{\sigma_y^2(x')} + \frac{H^2}{\sigma_z^2(x')}\right\} \tag{1-17}$$

where U_h is the wind speed at height H.

1.1.3.2 Modification for Deposition

Eq. (1-16) was modified to allow for removal of mass at the earth's surface by a method first described by Gregory [6]. The total amount of mass $Q_m(x)$ remaining in the cloud at distance x from its initial position was reduced by the amount deposited over that distance. Hence Q_m in Eq. (1-16) was replaced by

$$Q_m(x) = Q_m \exp - \frac{\Lambda x^{n/2}}{U_0} \tag{1-18}$$

where n is a parameter introduced by Sutton to describe the effects of stability variations on the vertical wind profile, and where Λ is a constant representing the mass removal rate or the mass fraction to peak concentration values in the direction of cloud movement Eq. (1-16) reduces to

$$\chi_m(\xi, y, 0, t) = \frac{2Q_m \exp - \Lambda x^{n/2} U_0^{-1}}{(2\pi)^{3/2} \sigma_x(x') \sigma_y(x') \sigma_z(x')} \exp - \frac{1}{2}\left\{\frac{y^2}{\sigma_y^2(x')} + \frac{H^2}{\sigma_z^2(x')}\right\} \tag{1-19}$$

1.1.3.3 Modification for Wind Shear

Because of the wide range of source heights and travel distances that must be considered in the toxic fuel diffusion problem, the model was modified to allow for systematic cloud deformation due to vertical wind shear. This modification was accomplished by evaluating Eq. (1-19) at points along the earth's surface determined by the mean wind speed and direction in the layer below the source. In order to simplify the computations Eq. (1-19) was re-written approximately in cylindrical polar coordinates as follows:

$$\chi_m(r', \delta\Theta', 0, t) = \frac{2Q_m \exp - \Lambda r^{n/2} U_0^{-1}}{(2\pi)^{3/2} \sigma_r(x')\sigma_\Theta(x')\sigma_z(x')} \exp - \frac{1}{2}\left\{\frac{H^2}{\sigma_z^2(x')} + \frac{(\delta\Theta)^2}{\sigma_\Theta^2(x')}\right\} \tag{1-20}$$

where r' = distance (m) from source to the ground-level position at which χ_m is evaluated and $\delta\Theta'$ is the angular distance (radians) between the cloud center-line at $z = 0$ and the radial line at which χ is evaluated. Note that $\sigma_\Theta(\chi')$ must now be expressed in radians in the exponential term.

With these modifications Eq. (1-17) for dosage takes the form

$$D(r', \delta\Theta', 0, t) = \frac{Q_m}{2\pi\sigma_\Theta(x')\sigma_z(x')U_H} \exp - \left(\frac{\Lambda r}{U_0}\right)^{n/2} \exp - \frac{1}{2}\left\{\frac{H^2}{\sigma_z^2(x')} + \frac{(\delta\Theta)^2}{\sigma_\Theta^2(x')}\right\} \tag{1-21}$$

Eq. (1-20) and (1-21) are valid only for cloud widths that are sufficiently narrow so that no serious error is involved in replacing σ_y by σ_Θ.

Conversion from the polar coordinate system r, $\delta\Theta$ at z = H to r', $\delta\Theta'$ at z = 0 was accomplished by the relations

$$r' = \frac{\overline{U}}{U_H} r \tag{1-22}$$

$$\delta\Theta' = \sum_{i=1}^{n} \left(\frac{\partial\varphi}{\partial z}\right)_i \Delta z_i + \delta\Theta \tag{1-23}$$

where $\overline{U}$ is the mean wind speed between the surface and z = H, and the summation in Eq. (1-23) is carried out over layers of constant wind direction shear $(\partial\varphi/\partial z)$ between the surface and z = H.

1.1.3.4 Layered Source Model

The normal launch exhaust plume and the static test firing plume cannot be realistically simulated by a single symmetrical source volume. In such applications multiple source volumes were used and the dosages resulting from the total cloud were obtained by linear superposition according to

$$D_t(r', \delta\Theta', 0, t) = \sum_{j=1}^{m} \frac{Q_{mj}}{2\pi\sigma_{\Theta j}(x_j')\sigma_{zj}(x_j')U_{Hj}} \exp - \left(\frac{\Lambda r_j}{U_0}\right)^{n/2} \exp - \frac{1}{2}\left\{\frac{H_j^2}{\sigma_{zj}^2(x_j')} + \frac{(\delta\Theta)_j^2}{\sigma_{\Theta j}^2(x_j')}\right\} \tag{1-24}$$

For the special case $m = 1$, $H = 0$, the average dose rate and the dosages for specified time periods, can be evaluated approximately from the total dosage values given by Eq. (1-24). If it is assumed that all material passing the point $(r', \delta\Theta', 0)$ is contained between $r' = \xi - 3\sigma_{r'}(z')$ and $r' = \xi + 3\sigma_{r'}(x')$, the total time for passage of this material is

$$\Delta\tau = \frac{6\sigma_{r'}(x')}{U_0} \tag{1-25}$$

and the average dose rate $\overline{D} = D/\Delta\tau$.

The average dose rate $\overline{D}$ (T) for a specified time interval T is given by the equation

$$\overline{D}(T) = FD/T \tag{1-26}$$

where F is the fraction of D contained between the abscissas $r = \pm U_0 T$ of a normal distribution function centered at $r = 0$ and with standard deviation $\sigma_{r'}(x')$.

1.2 Application of Models to Diffusion Problems at Marshall Space Flight Center, Huntsville, Alabama.

1.2.1 Introduction

Specifications were provided for two potential source modes at the Marshall Space Flight Center (MSFC), Huntsville, Alabama. The first of these was the exhaust plume that results from static vehicle firing tests. Exhaust gases at high temperatures, emitted downward as a jet from the vehicle, strike cooled plates and are deflected outward and upward from the point of origin. As the gases leave the deflector channel, momentum gained during the initial release rapidly gives way to buoyant ascent resulting in a quasi-vertical plume that may reach altitudes of several thousand feet. The ascent terminates as the plume gases approach ambient densities by entrainment or eddy heat conduction processes and radiative cooling.

The second source mode of concern was that due to inadvertant spill of liquid fluorine on or near the firing test site. During the brief time interval before the spill or leak can be stopped a certain fraction of all liquid released to the atmosphere will be converted to fluorine vapor (F_2) that will rapidly mix with air to form the source cloud. The possible conversion of some liquid fluorine to hydrogen fluoride (HF) accompanied by the release of heat was not considered at this time.

A detailed description of the test site and the region surrounding it including a topographic chart is presented in Part 2 of this report. Source parameters, meteorological data, and the results of selected diffusion model computations are given in Sections 1.22, 1.23, and 1.24. The shortcomings of the model and suggestions for refinement are described at the end of Part 1 (Section 1.3).

1.2.2 Diffusion Model Source Specifications

1.2.2.1 Static Firing Tests

The cloud rise models described in Section 1.1.2 require numerical values of the excess amount of heat contained within the cloud at the moment of release into the atmosphere, the ambient vertical temperature gradient, and the mean wind speed. Quantitative information on mechanical deflection of the exhaust jet is needed also for static firing tests.

Rough estimates of the shape, dimensions, and height of rise of the visible plumes from static firing tests of various durations were taken from motion pictures provided on loan by MSFC. The altitudes at which measurable departures of plume angle from the blast deflector angle occurred were determined from these photographs for selected source strengths. Specifications of fuel amount and exhaust temperature provided for four vehicles (A, B, C, and D) by MSFC were used as initial conditions for static firing tests at MSFC. It was assumed that the exhaust temperature (2500°F) was valid at the termination of the jet phase of plume rise. The excess heat of hydrogen fluoride (HF) at this point was computed from the heat content of the gas at 2500°F (8.31×10^3 cal. mole^{-1}, Lewis and von Elbe [10]). First approximations to the height of buoyant rise of the plume were obtained from Eq. (1-9) using a mean wind speed of 6.5 m sec^{-1}. To these were added the estimated plume heights at the end of the jet phase.

TABLE 1-2(a)
STATIC FIRING TEST SOURCE PARAMETERS

Vehicle	Total emission lbs (HF)	Excess heat megawatts	Buoyant rise (m)	Jet rise (m)	Stabilization height (m)
A	35,080	1,120	430	300	730
B	86,550	2,950	540	400	940
C	169,700	5,810	650	500	1150
D	418,700	14,340	810	600	1410

The horizontal dimension σ = a of the plume at stabilization height was derived from Eq. (1-11) using C = 0.45, m = 1.75 and height values from Table 1-2(a). With this dimension and the height of stabilization as guidelines a simple inverted teardrop shape was assumed. The lower part of the plume was modeled as a paraboloid and the upper part as a hemisphere. The standard deviations of horizontal bivariate normal distribution of mass at each of six levels are shown schematically in Fig. 1-1. The heights of each level and the corresponding values of lateral standard deviation σ_y for the four vehicles are listed in Table 1-2(b).

TABLE 1-2(b)
ASSUMED LATERAL STANDARD DEVIATIONS σ_y AND CORRESPONDING HEIGHTS FOR STATIC FIRING TEST PLUMES FROM 4 VEHICLES

	Vehicle A		Vehicle B		Vehicle C		Vehicle D	
Level	Height (m)	σ_y (m)	Height (m)	σ_y (m)	Height (m)	σ_y (m)	Height (m)	σ_y (m)
1	220	0	260	0	280	0	250	0
2	350	64	430	86	500	110	540	150
3	480	90	600	120	720	150	830	210
4	600	110	770	150	930	190	1120	250
5	730	130	940	170	1150	220	1410	290
6	860	0	1120	0	1360	0	1700	0

It should be kept in mind that no measurements of either vertical or horizontal concentration profiles in actual test plumes were available. Consequently, the distributions in Table 1-2 are essentially hypothetical models constrained by rough estimates of heat source strengths and the visual appearance of test plumes on film. Because of the horizontal component of motion of the exhaust jet and the action of vertical wind shear, actual test plumes are not

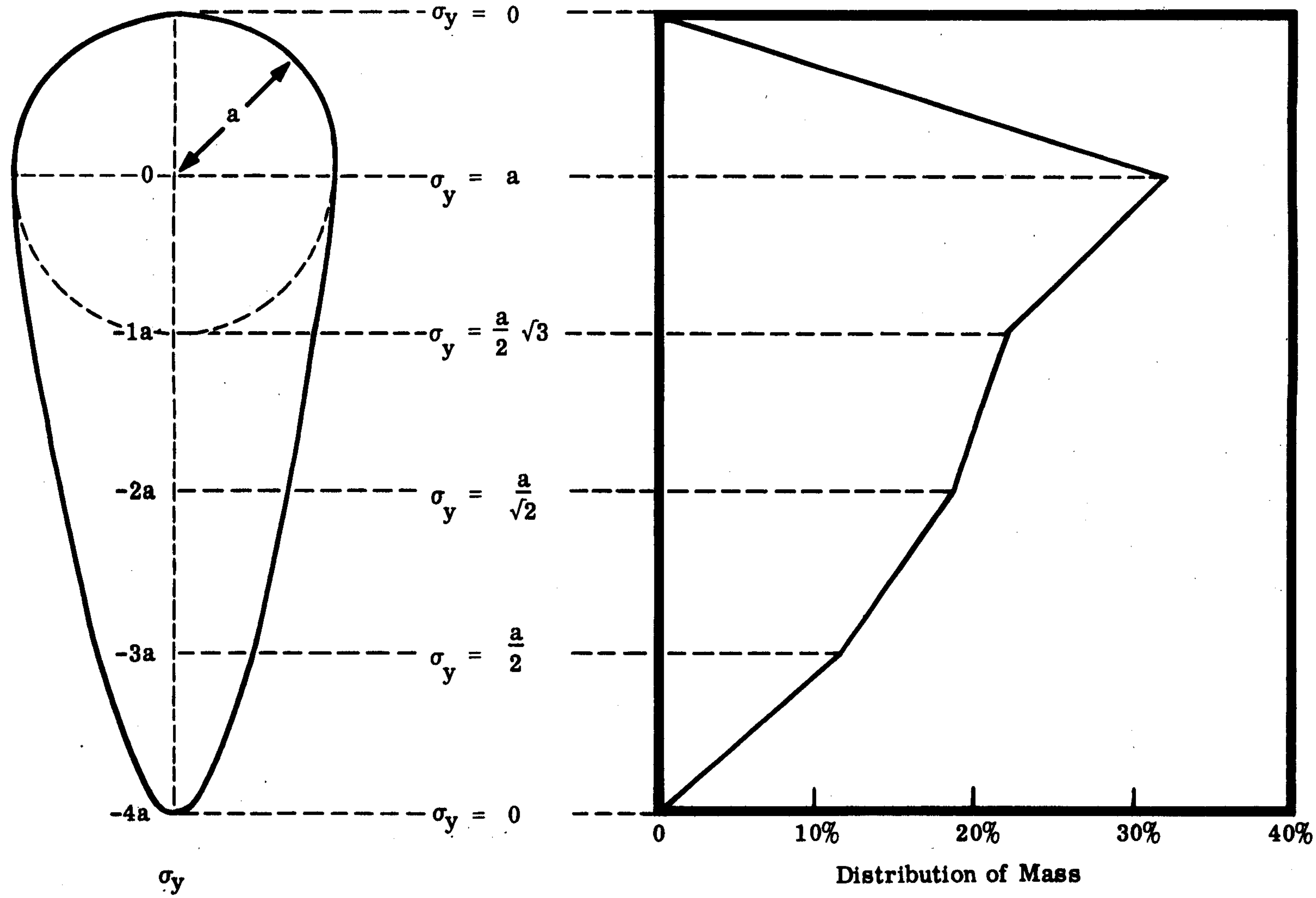

Fig. 1.1. Assumed vertical profiles of lateral standard deviation σ_y and mass for static firing test source plume. The origin of the vertical axis is at the computed height of cloud stabilization.

vertical. However, since the deviations from the vertical are small compared with distances of interest in this problem these effects were neglected in the preliminary source plume model.

1.2.2.2 Spill Sources

It was assumed that cold liquid spills due to pipeline leakage or other sources would be transformed instantaneously into a vapor cloud at ground level. No buoyant rise of the cloud was permitted. This assumption requires a more thorough investigation because of the possibility of effective cloud rise due either to heat generated by partial combustion of the liquid fluorine or to the density deficit relative to the environment of the initial incompletely mixed fluorine vapor.

A second assumption was invoked in modeling the spill release as a continuous point source. For spill areas with dimensions of the order of tens of meters on a side this assumption is reasonable for concentration or dosage calculations at distances of 1 km or more. However, for very large spill areas, or at short distances, the finite dimensions of the source should be taken into account.

Within the limits for which these assumptions are reasonable the computed concentrations and dosages, expressed in terms of unit source strength, can be converted by straightforward multiplication to any desired source strength.

1.2.3 Meteorological Specifications

The gas or vapor clouds formed either by static firing or as a result of spills are formed in short time periods of a few minutes or less and are then carried by the wind as puffs or clusters. Ground-level concentrations and dosages that result from the overhead passage of the cloud are critically dependent on its dimensions at the time of passage. In the diffusion model described in Section 1.1.3 the cloud dimensions as measured by the standard deviations of a normal distribution must be specified as functions of distance

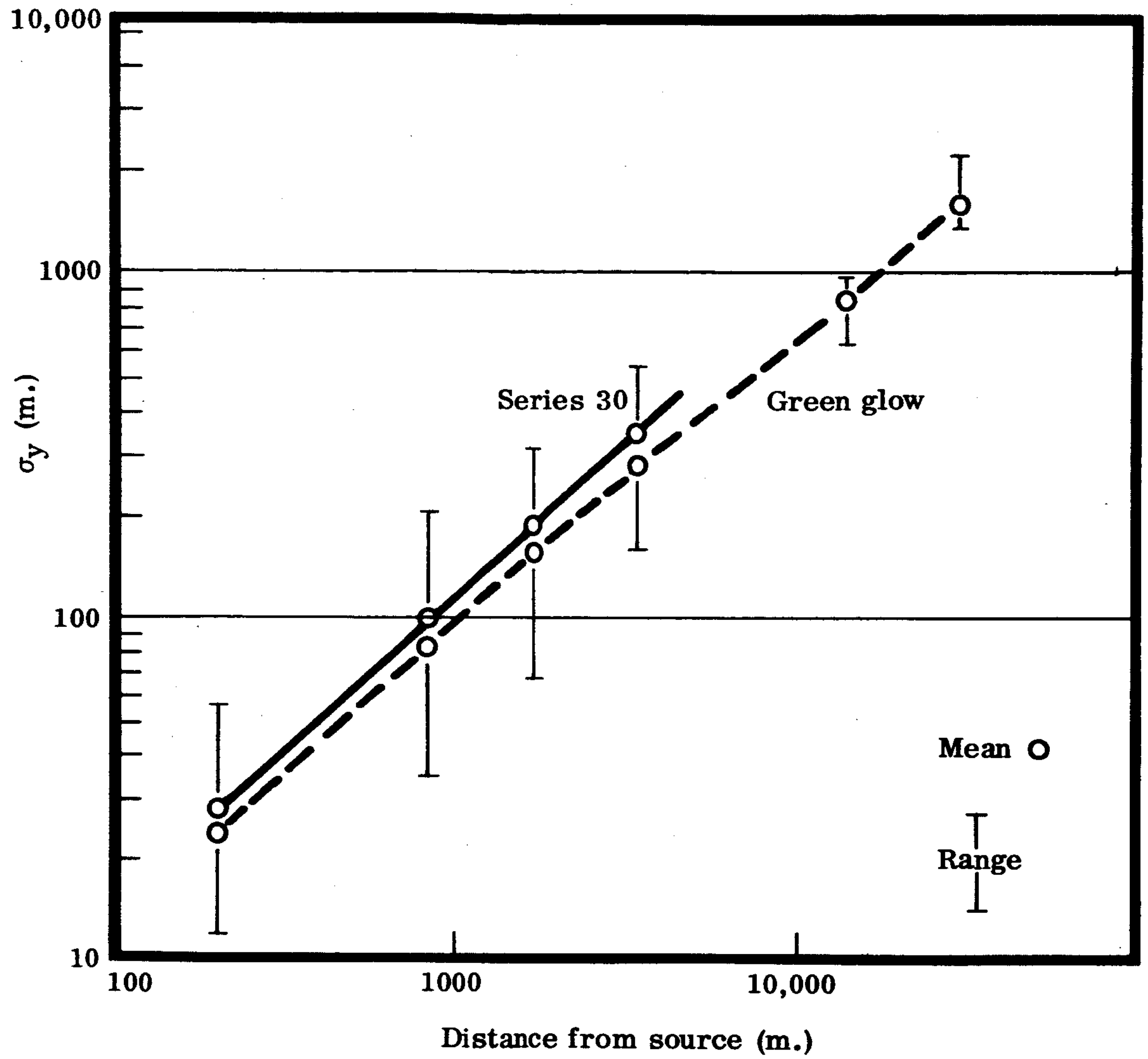

Fig. 1.2. Lateral standard deviations (σ_y) of FP in "Series 30" and "Green-glow" experiments at Hanford, Washington from Fuquay, Simpson, Barad, and Taylor [5].

from the source. For this purpose it would be desirable to have actual concentration measurements taken along horizontal and vertical axes in moving puffs under a variety of stability conditions and for various distances from the source in the Huntsville area. Such measurements were not available and it was necessary to use experimental data from other sites to meet this requirement.

A comprehensive review of experimental measurements of cloud dimensions from low-level diffusion experiments with smoke puffs, gases, and fine aerosols was carried out. Sources of data included Bosanquet [1], Bowne [2,3], Cramer [4], Haugen and Fuquay [5], Hilst [8], Högström [9], Islitzer [10], Fuquay, Simpson, Barad, and Taylor [5], Pasquill [14,15], Scoggins [17], and Stewart, et al. [19]. These data were classified grossly according to terrain and atmospheric stability conditions. An example of measurement of the lateral (arcwise) standard deviations of fluorescent particle (ZnS) clouds from 15 experiments under both stable and unstable conditions is shown in Fig. 1-2 taken from Fuquay, et al., [5]. In each test the particles were released continuously for 30 minutes into a basin area and samples were taken at a height of 1.5 m along 4 arcs to a distance of 3.2 km from the source. A second example based on experiments in the National Reactor Testing Station area in Idaho is shown in Fig. 1-3. In these tests uranine dye was released for 30 min. periods from a 150 ft tower under unstable conditions. Samples were taken near ground level along arcs to a distance of 1.8 km from the source.

Guidance for the selection of appropriate values of the standard deviation of concentration along the vertical axis at various distances from the source was obtained primarily from the tentative graphical summary given by Pasquill [14,15], Fig. 5-7, p. 209. As pointed out by the author, the values in the graph are essentially speculative at extreme stabilities and at large distances. The graph was intended for use with short duration sources (emission times of the order of a few minutes) in open country.

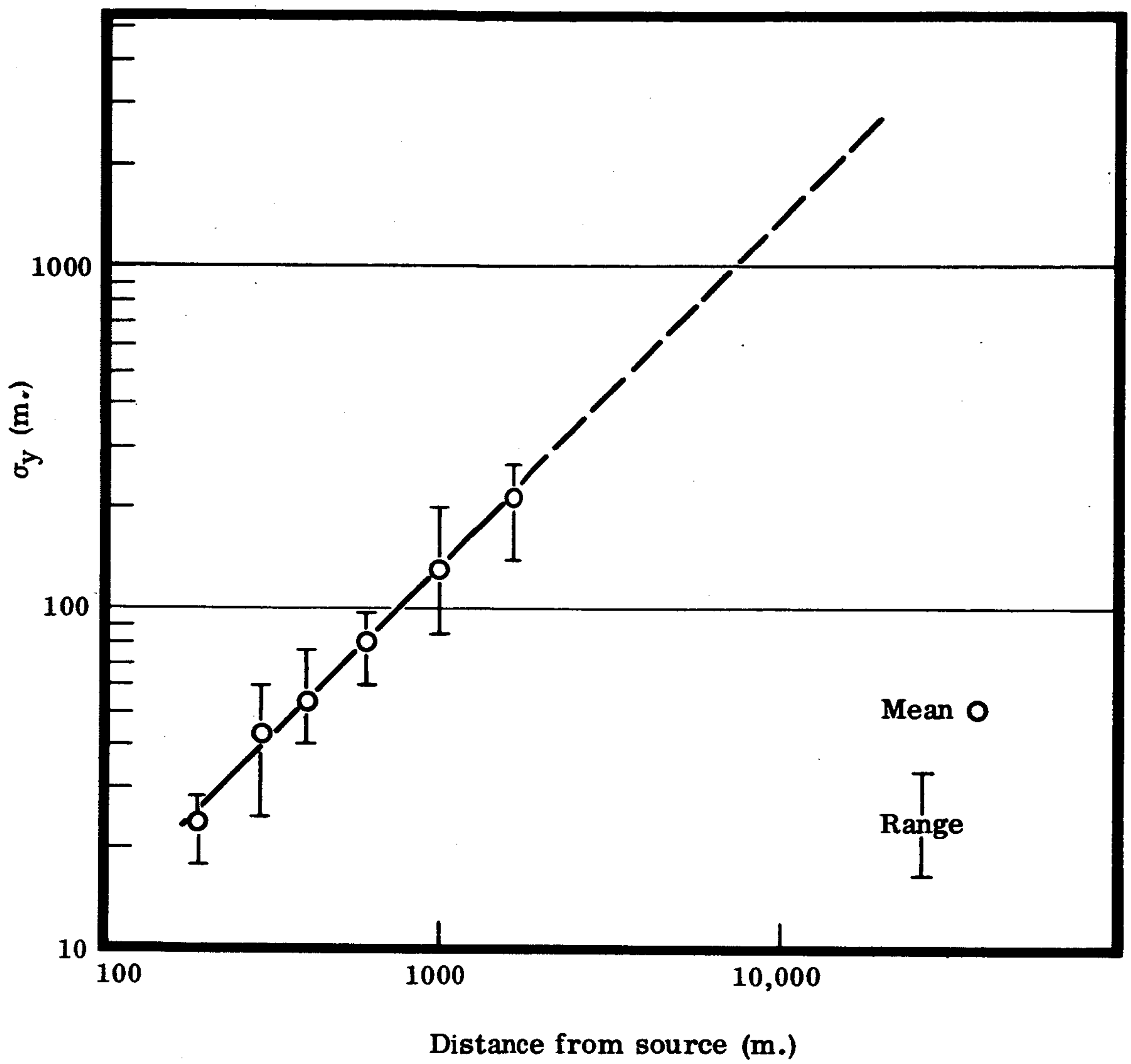

Fig. 1.3. Lateral standard deviations (σ_y) of uranine dye in experiments at the National Reactor Testing Station, Idaho from Islitzer [10].

Lateral and vertical standard deviations of concentration were selected for 3 classes of dilution rate labelled maximum dilution (temperature lapse rate equal to or greater than dry adiabatic), average dilution (temperature lapse rate less than adiabatic but greater than or equal to the standard atmosphere rate) and minimum dilution (temperature lapse rate less than standard atmosphere but greater than isothermal). These values are tabulated at intervals of 1 km from the source in Table 1-3.

In all calculations described at this time, it was assumed that the standard deviation $\sigma_r(x')$ Eq. (1-20) of concentration along a radial axis from the source was equal to the lateral standard deviation at the same distance. No attempts were made to include vertical variations in the standard deviations.

Typical wind profiles corresponding to each of the three dilution classes defined above were obtained from a summary of late afternoon (local time) rawinsonde data supplied by personnel at MSFC for the year 1963. Average speeds and directions for each temperature gradient category are shown in Fig. 1-4. It should be kept in mind that the dilution class labels were based on the magnitudes of the standard deviations in Table 1-3 and that these labels are not necessarily consistent with the expected diluting effects of wind shear.

1.2.4 Results

1.2.4.1 Static Firing Tests

The diffusion model represented by Eq. (1-20) and the auxiliary equations (1-22) and (1-23) was programmed for use on an IBM 1620 computer with provisions for summing contributions from one to six source levels. The input control data for static firing tests were obtained from Tables 1-2(a) and 1-2(b) for the source and from Table 1-3 and Fig. 1-4 for meteorological conditions. The summed ground-level concentrations from all source layers were plotted on plane polar projections and analyzed for the location and magnitude of the cloud centerline at ground level. Centerline concentrations in units of parts of

TABLE 1-3
VALUES OF LATERAL STANDARD DEVIATION (σ_y) AND VERTICAL STANDARD DEVIATION (σ_z) USED FOR COMPUTATIONS OF CLOUD GROWTH BY DIFFUSION AT MSFC

Distance (km)	Maximum σ_y (m)	Dilution σ_z (m)	Average σ_y (m)	Dilution σ_z (m)	Minimum σ_y (m)	Dilution σ_z (m)
1	190	380	120	120	68	68
2	340	680	220	220	125	120
3	480	960	310	310	180	170
4	620	1240	400	400	235	220
5	745	1490	480	480	275	260
6	860	1720	560	560	325	305
7	980	1960	645	645	370	340
8	1100	2200	735	735	420	380
9	1220	2440	825	825	460	420
10	1340	2680	915	915	500	455
11	1460	2920	1000	1000	548	498
12	1570	3140	1080	1080	582	523
13	1690	3380	1160	1160	630	567
14	1795	3590	1230	1230	670	592
15	1900	3800	1305	1305	710	637

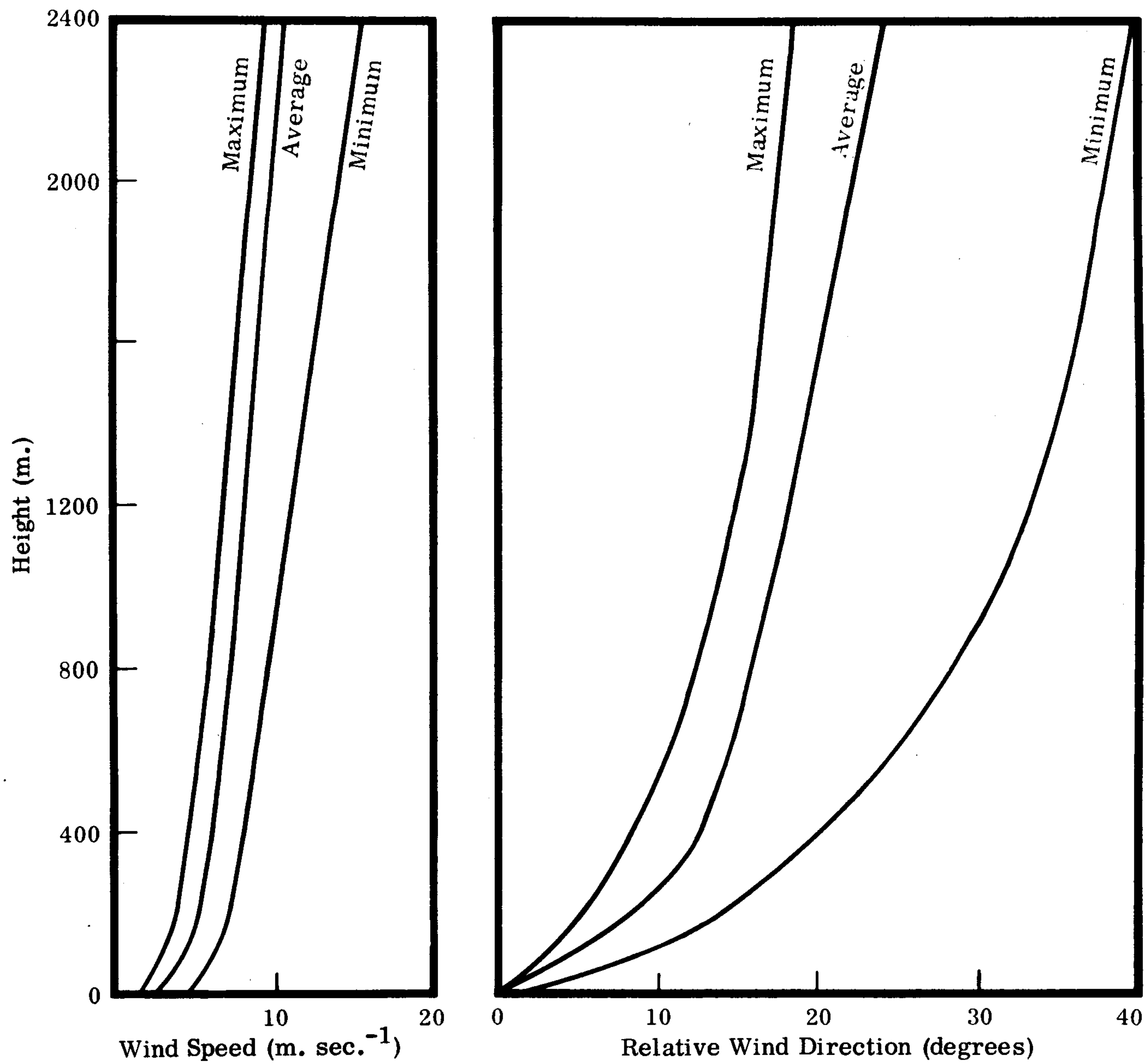

Fig. 1.4. Assumed wind profiles for maximum, average, and minimum dilution classes at MSFC.

hydrogen fluoride (HF) per million parts of air by weight per gram of source are shown as a function of distance from the source for each vehicle and for each dilution class in Figs. 1-5 to 1-8. Note that distances in these figures are from the true source position whereas the vertical and lateral standard deviations needed as input in Eq. (1-20) were referred to distances x' from the virtual source.

In each of Figs. 1-5 to 1-8 a smooth curve was drawn through the ground-level concentration pattern centerline values obtained by analyses as described above. Centerline concentrations were labelled as smoothed peak concentrations since they represent the expectation of a series or ensemble of quasi-instantaneous source tests. In any single test, particularly at short distances from the source, the peak concentration experienced at an observation point may differ greatly from the expected value. Further work is needed to provide estimates of the magnitude of such fluctuations as a function of distance from the source.

Although the concentrations in Figs. 1-5 to 1-8 are expressed in terms of unit source strength, caution must be used in extrapolating the numerical values to source strengths other than those specified by MSFC since a change in mass source strength may be accompanied by changes in the momentum of the deflected exhaust jet and in the amount of buoyant rise of the initial cloud.

The principal features of Figs. 1-5 to 1-8 may be summarized as follows:

(a) In progressing from maximum cloud dilution conditions to minimum dilution for all vehicle source strengths, the position of the maximum value of smoothed peak centerline concentration moved away from the source and the magnitude of the maximum decreased by one to two orders of magnitude. For the largest vehicle, the maximum value occurred at distances in excess of 15 km under minimum dilution conditions.

(b) Under both maximum and average dilution conditions as the source strength was increased progressively from vehicle A to vehicle D, the maximum value of smoothed peak centerline concentration diminished slightly indicating that the effect of increased mass of HF was more than compensated at ground level by the increased source height. Under minimum dilution conditions, however, increases in source height from vehicles A to B resulted in smaller peak concentrations at ground level but further increases in mass source strength from vehicle B to C and D more than compensated for the increased source height effect.

In Fig. 1-9 isopleths of smoothed peak concentrations at ground level have been superimposed on a topographic chart of the MSFC and Huntsville area. The assumed source area is indicated by a solid circle in the lower left corner of each figure. Concentration patterns are illustrated only for average dilution conditions as defined in Section 1.2.3.

It appears probable that the major topographical feature in Fig. 1-9 will result in large distortions of the idealized pattern shown by the contours. In its present form the diffusion model contains no provision for the effects of horizontal variations in the transporting wind field.

1.2.4.2 Spill Sources

Total dosages at ground level downwind from a liquid spill source are shown as functions of distance from the source in Fig. 1-10(a) for minimum dilution conditions and in Fig. 1-10(b) for maximum dilution conditions. Corresponding curves for non-zero values of Λ, the deposition coefficient, are included for the figures. In all cases the dosages are expressed in units of parts of fluorine gas (F_2) per million parts of air by weight times time (secs) per gram of F_2 released at the source. As noted previously a point source at ground level was assumed for these calculations. Within the limits for which this assumption is valid, the numerical values in Fig. 1-10 may be used with any total source strength.

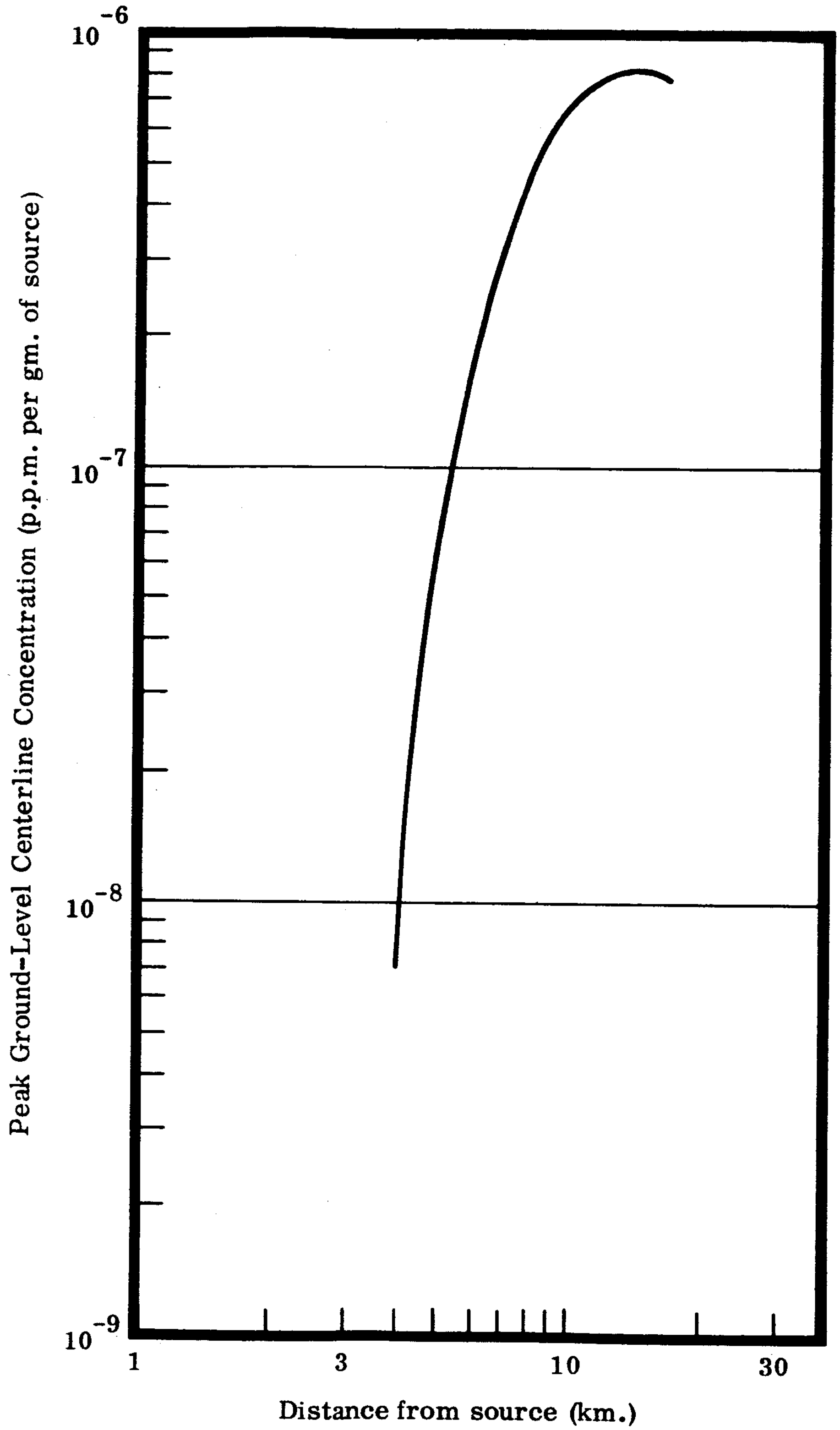

Fig. 1.5. Smoothed peak centerline concentrations at ground level as function of distance from a test firing of vehicle A.

(a) Minimum dilution conditions.

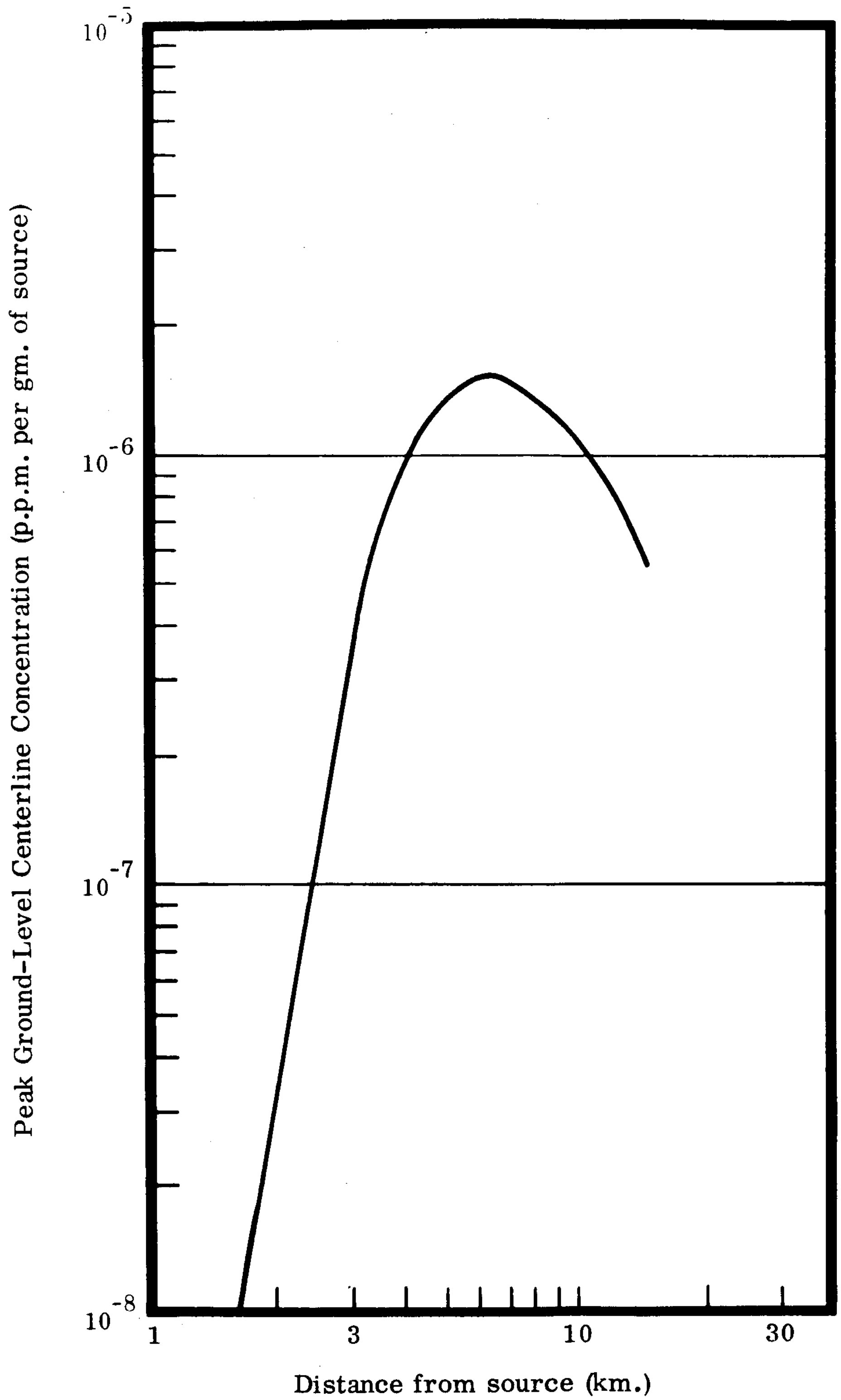

Fig. 1.5. Con't. (b) Average dilution conditions.

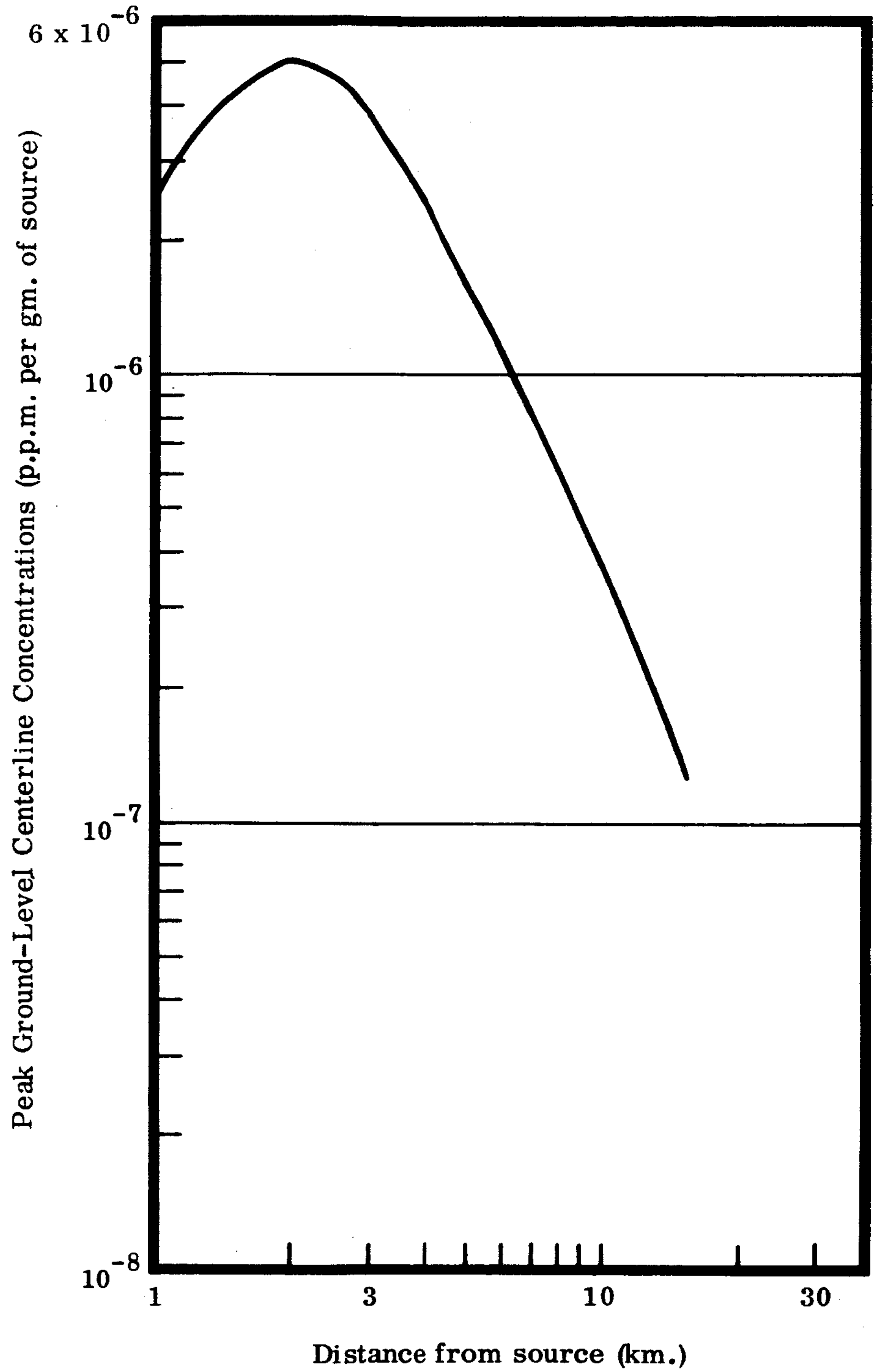

Fig. 1.5. Con't. (c) Maximum dilution conditions.

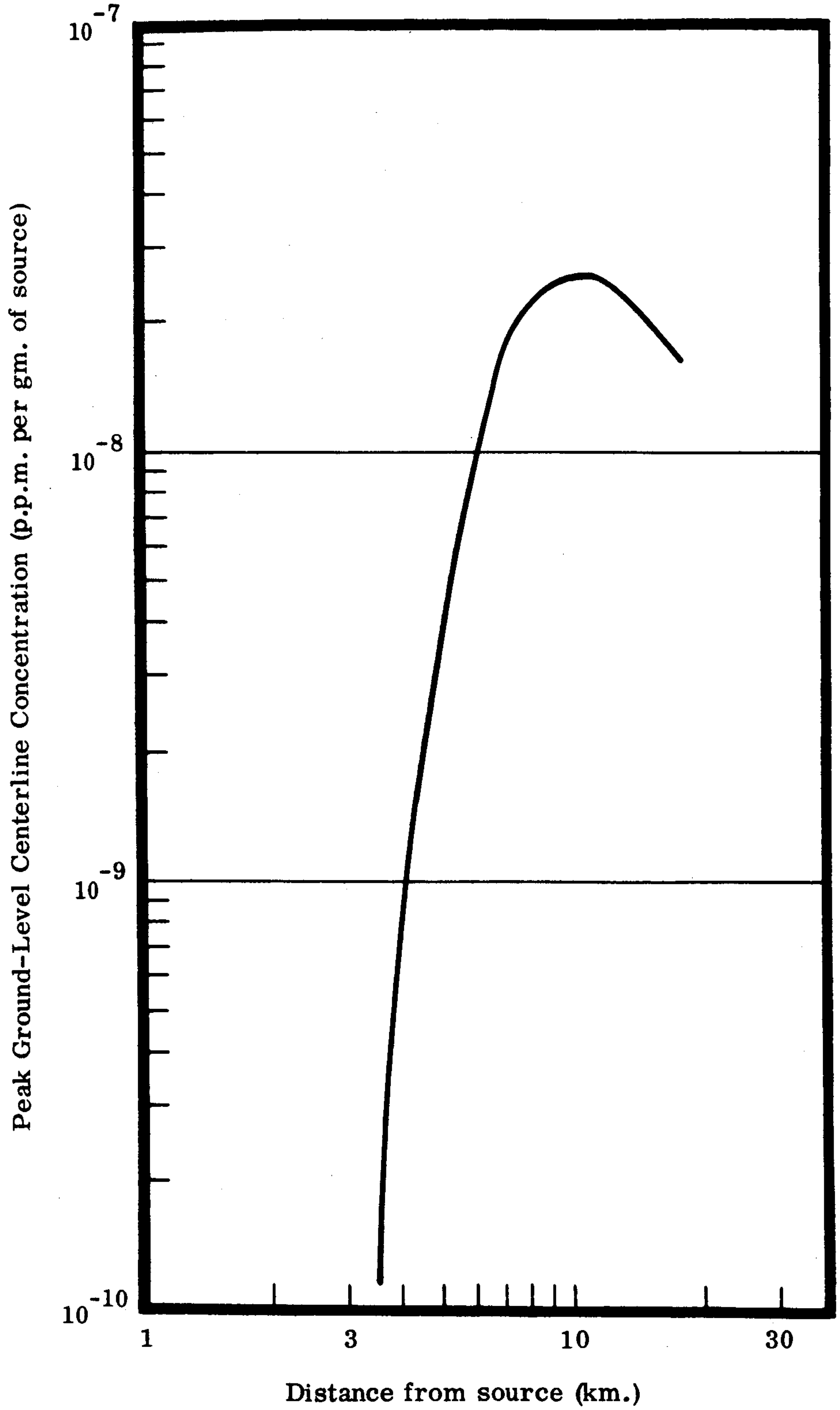

Fig. 1.6. Smoothed peak centerline concentrations at ground level as a function of distance from a test firing of vehicle B.

(a) Minimum dilution conditions.

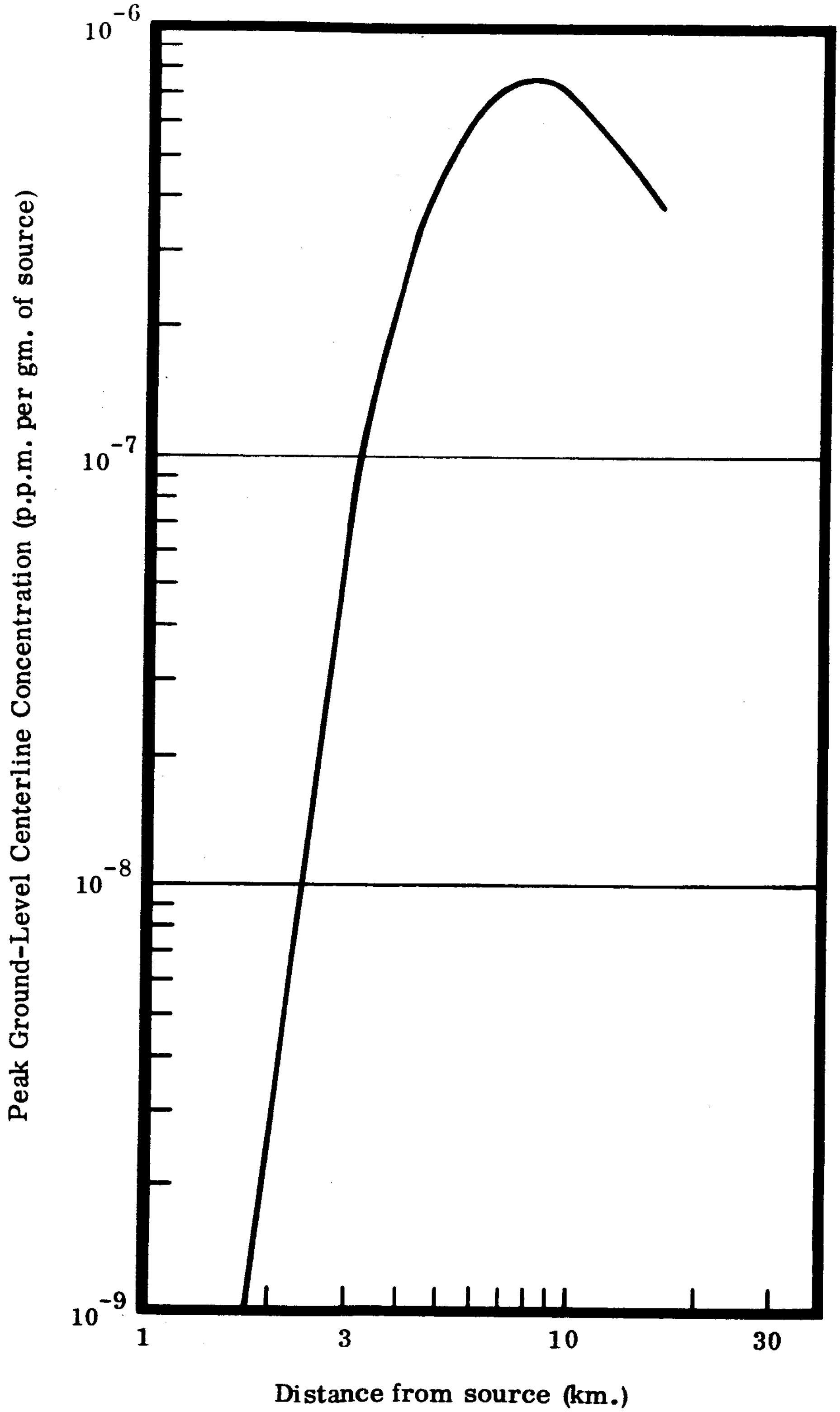

Fig. 1.6. Con't. (b) Average dilution conditions.

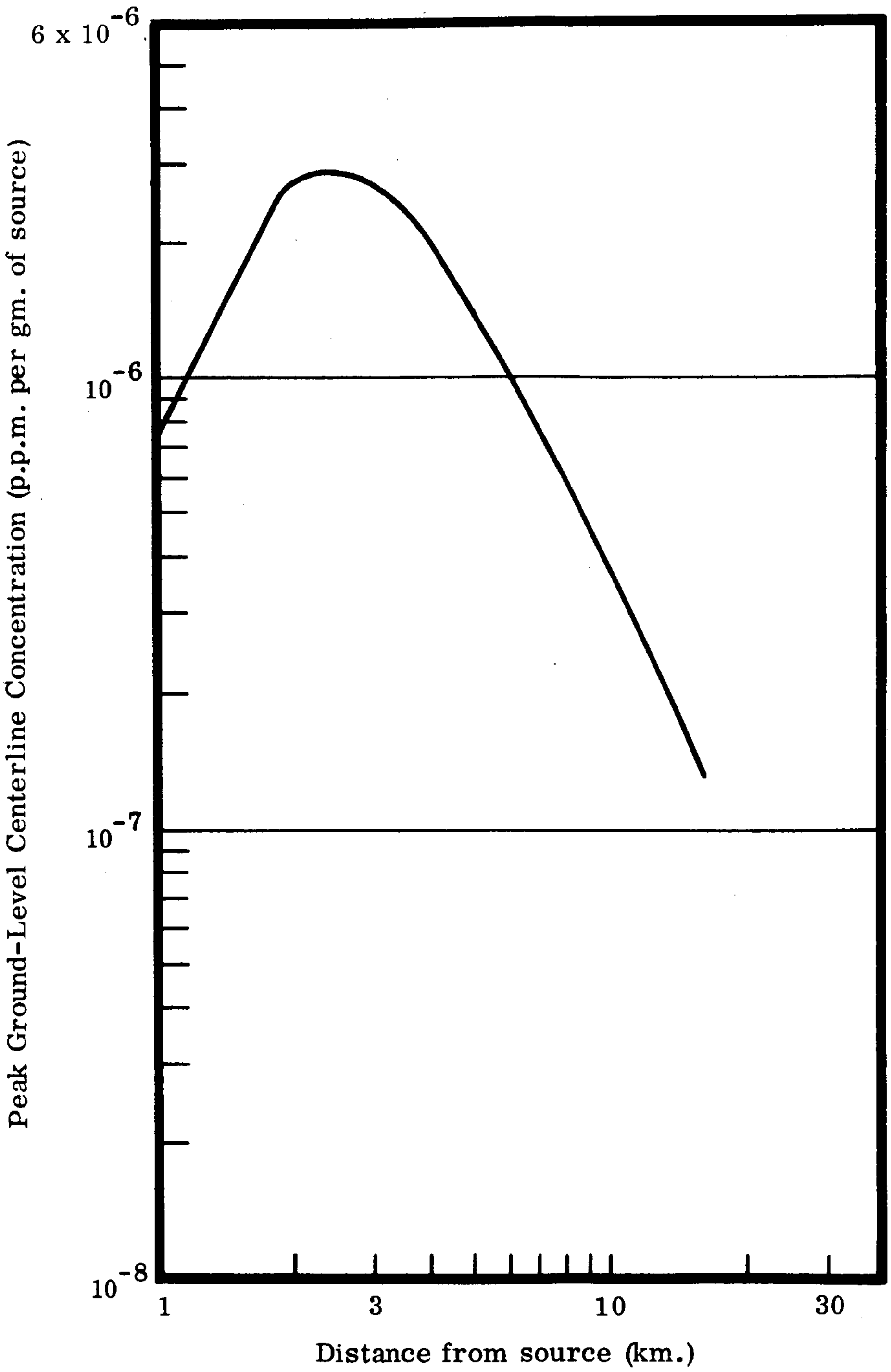

Fig. 1.6. Con't. (c) Maximum dilution conditions.

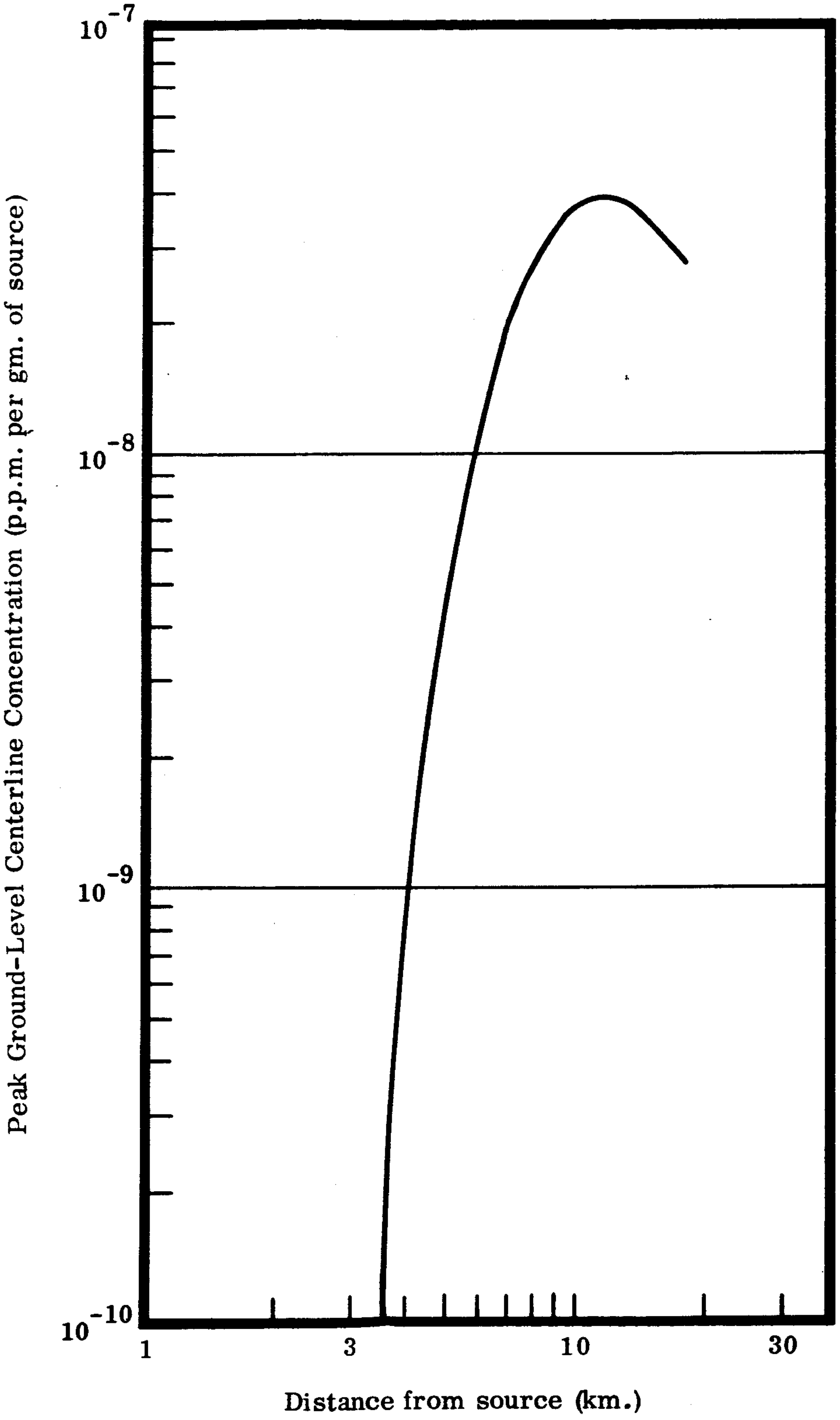

Fig. 1.7. Smoothed peak centerline concentrations at ground level as a function of distance from a test firing of vehicle C.

(a) Minimum dilution conditions.

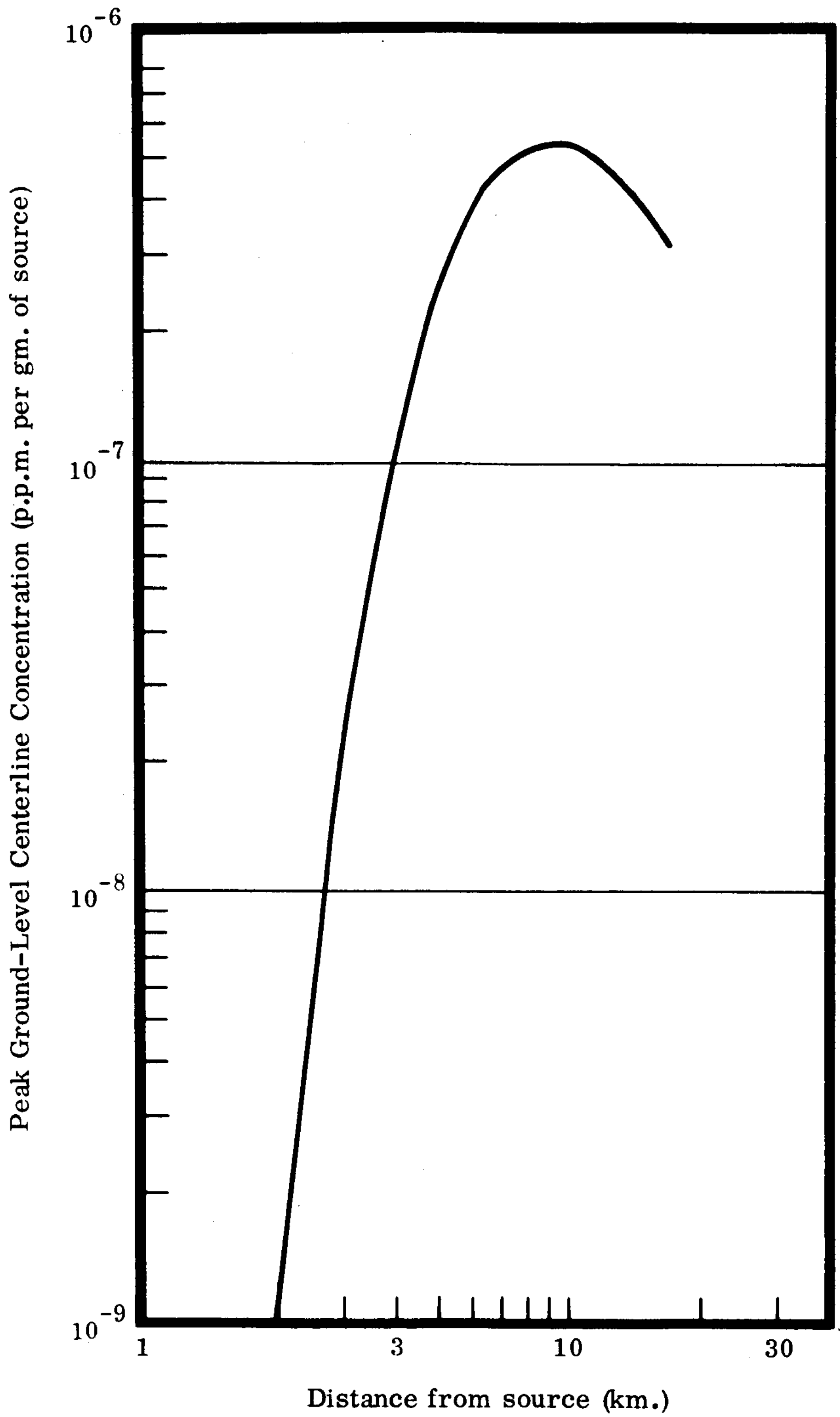

Fig. 1.7. Con't. (b) Average dilution conditions.

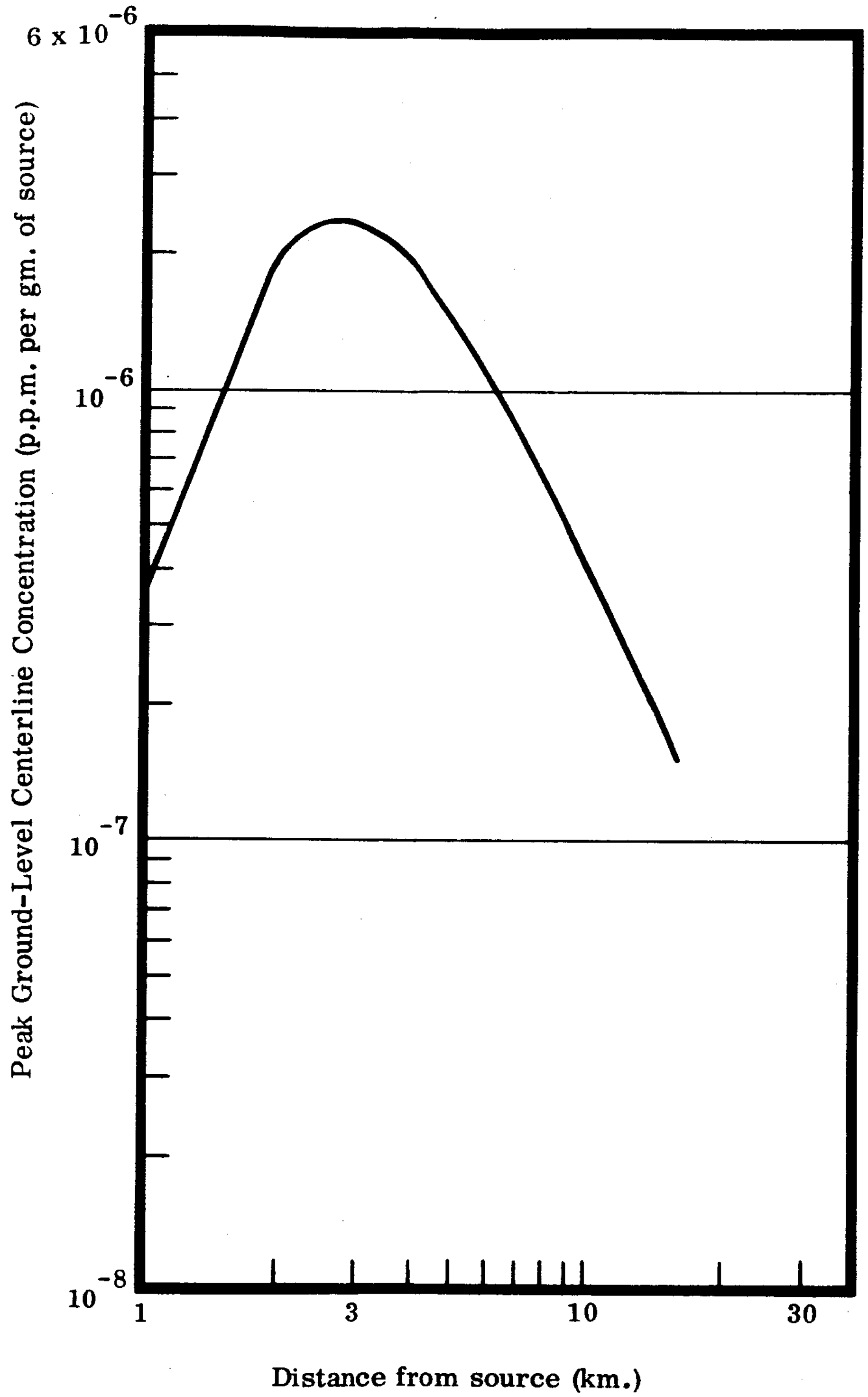

Fig. 1.7. Con't. (c) Maximum dilution conditions.

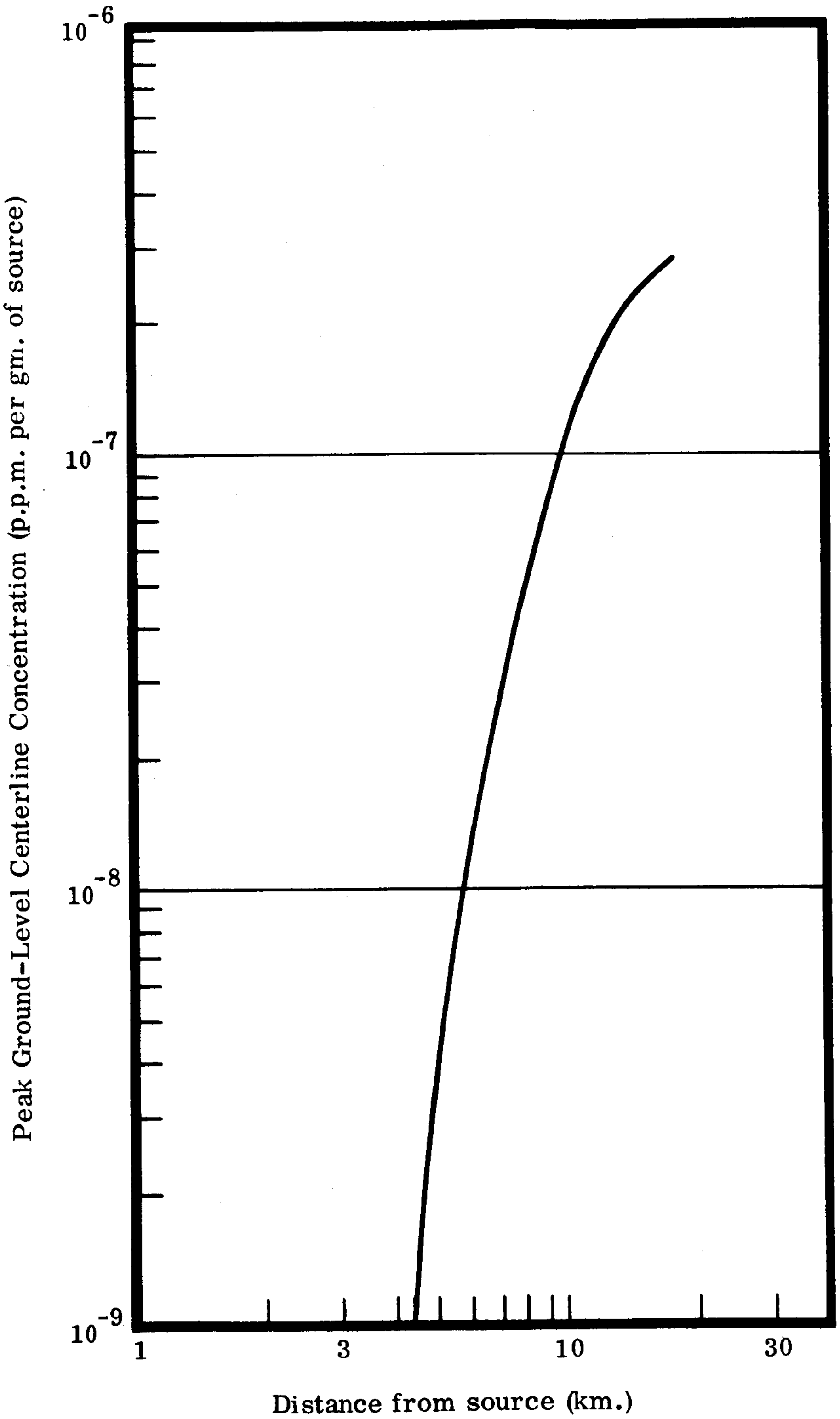

Fig. 1.8. Smoothed peak centerline concentrations at ground level as a function of distance from a test firing of vehicle D.

(a) Minimum dilution conditions.

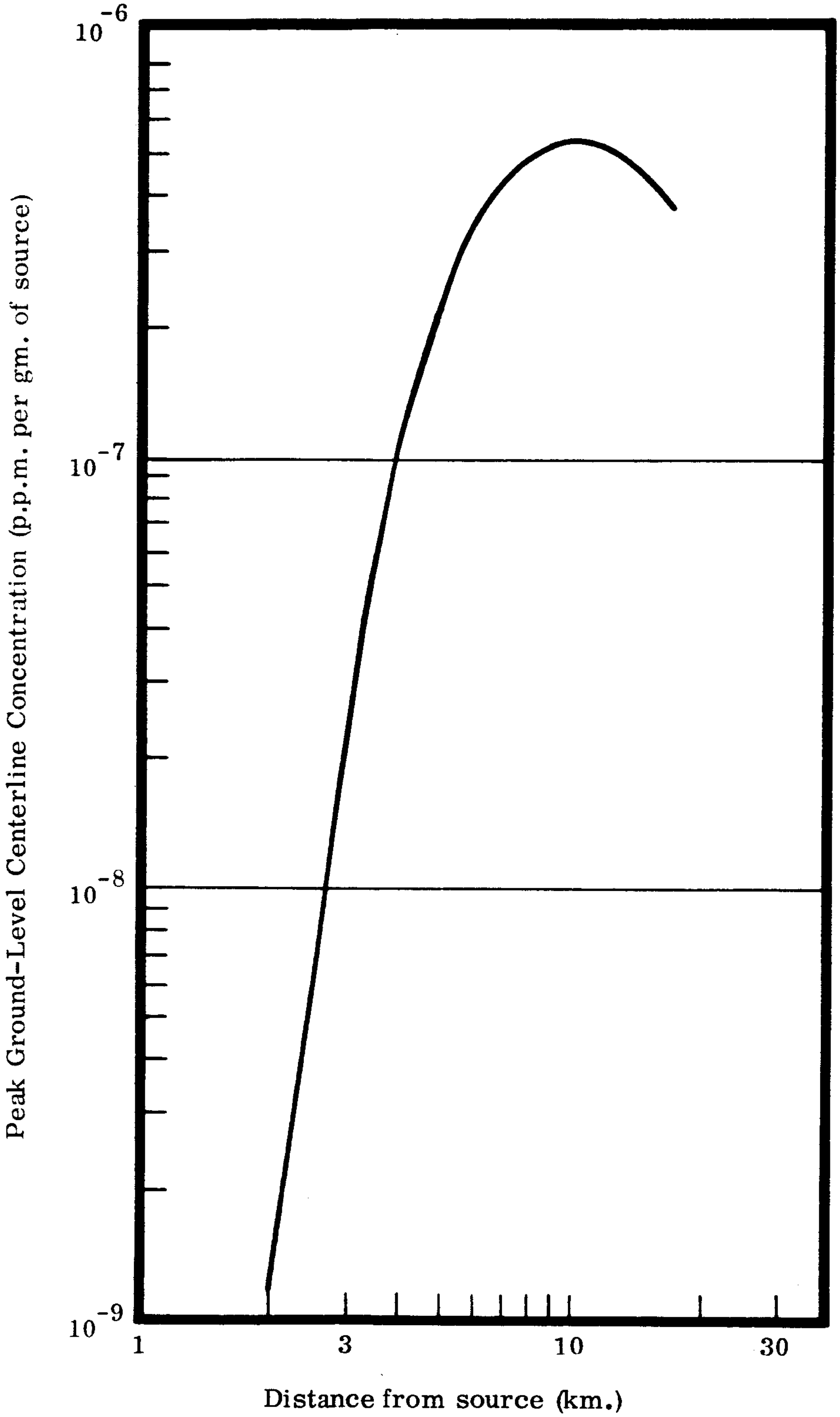

Fig. 1.8. Con't. (b) Average dilution conditions.

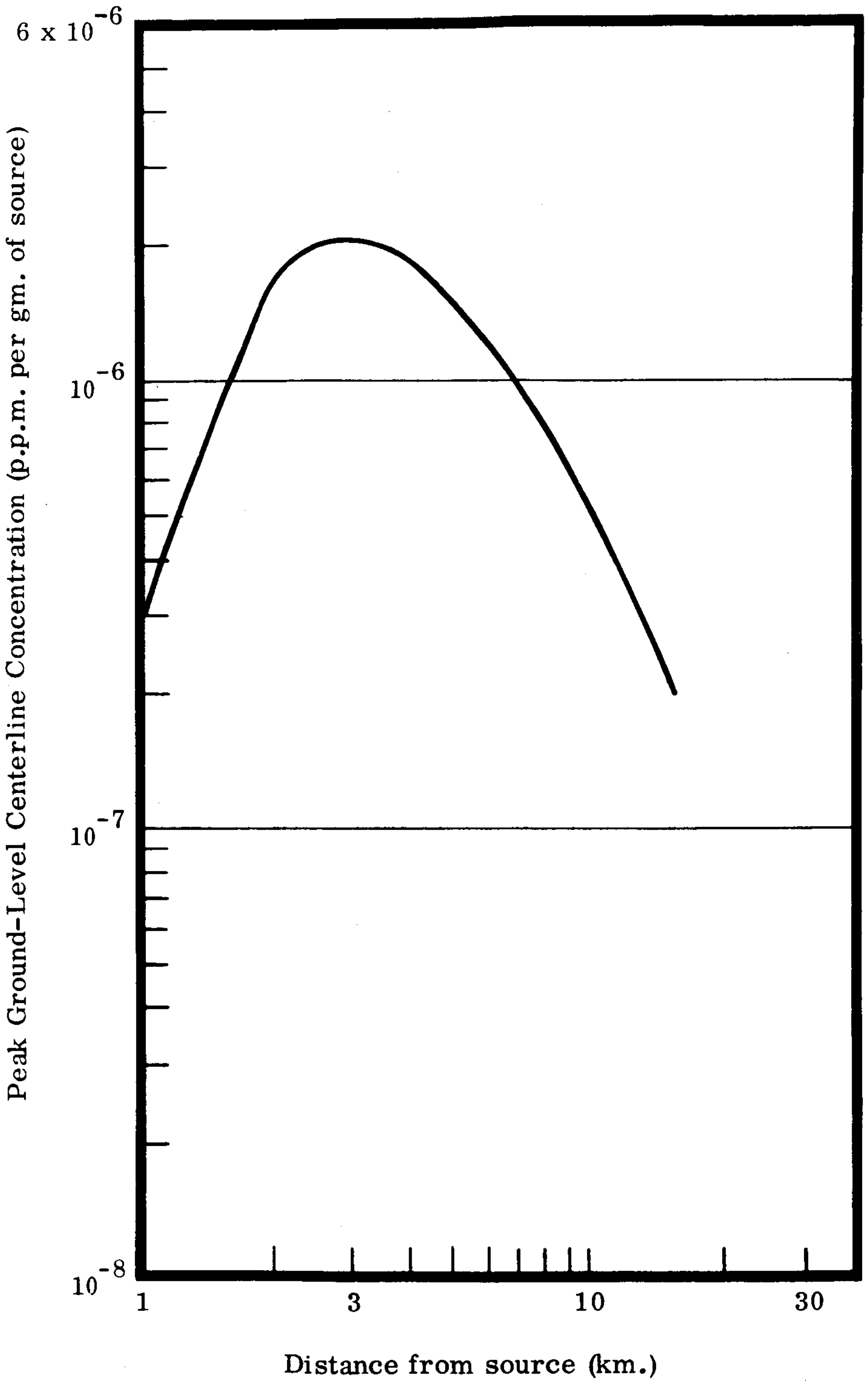

Fig. 1.8. Con't. (c) Maximum dilution conditions.

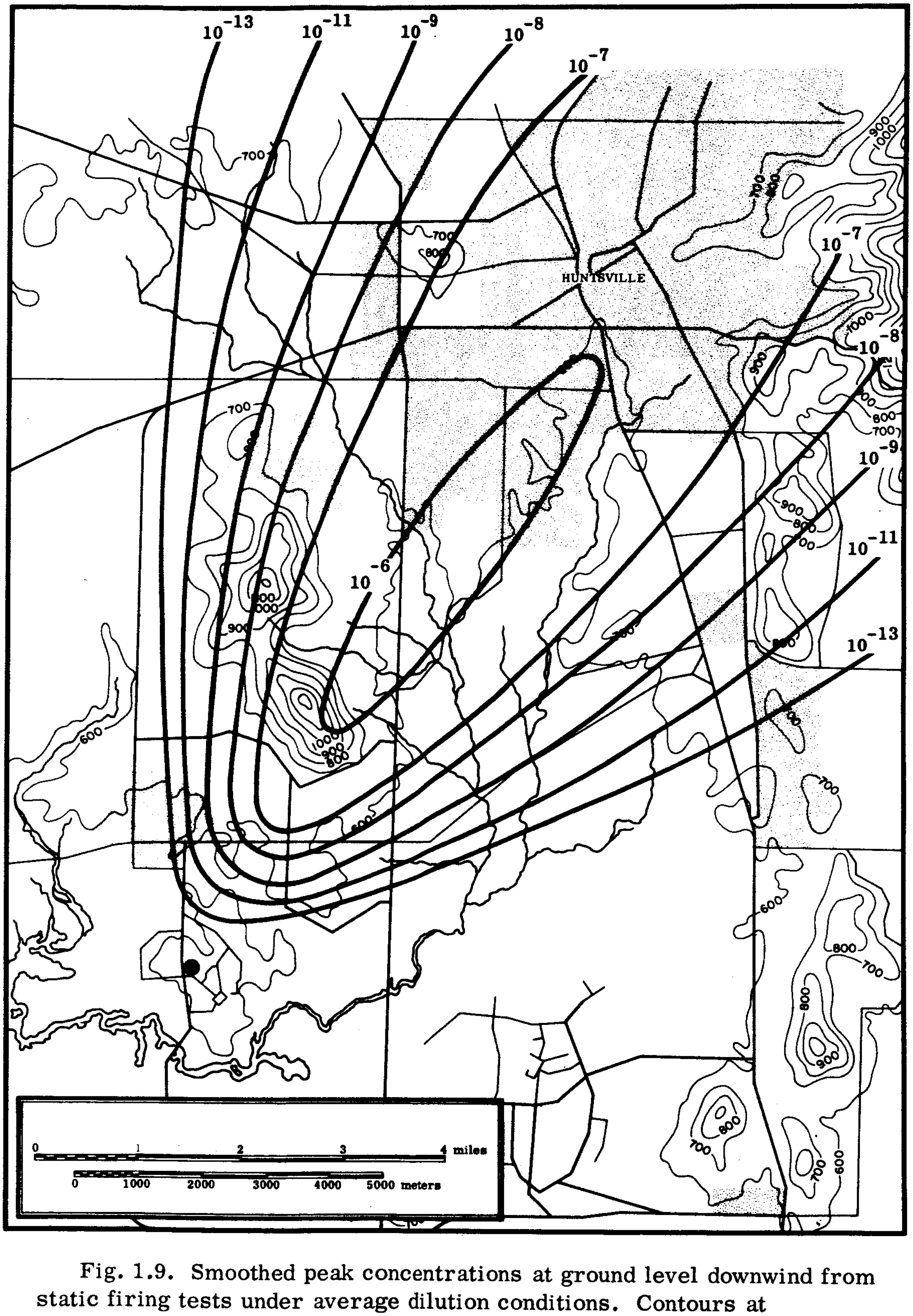

Fig. 1.9. Smoothed peak concentrations at ground level downwind from static firing tests under average dilution conditions. Contours at multiples of 10 ppm per gm of source.

(a) Vehicle A.

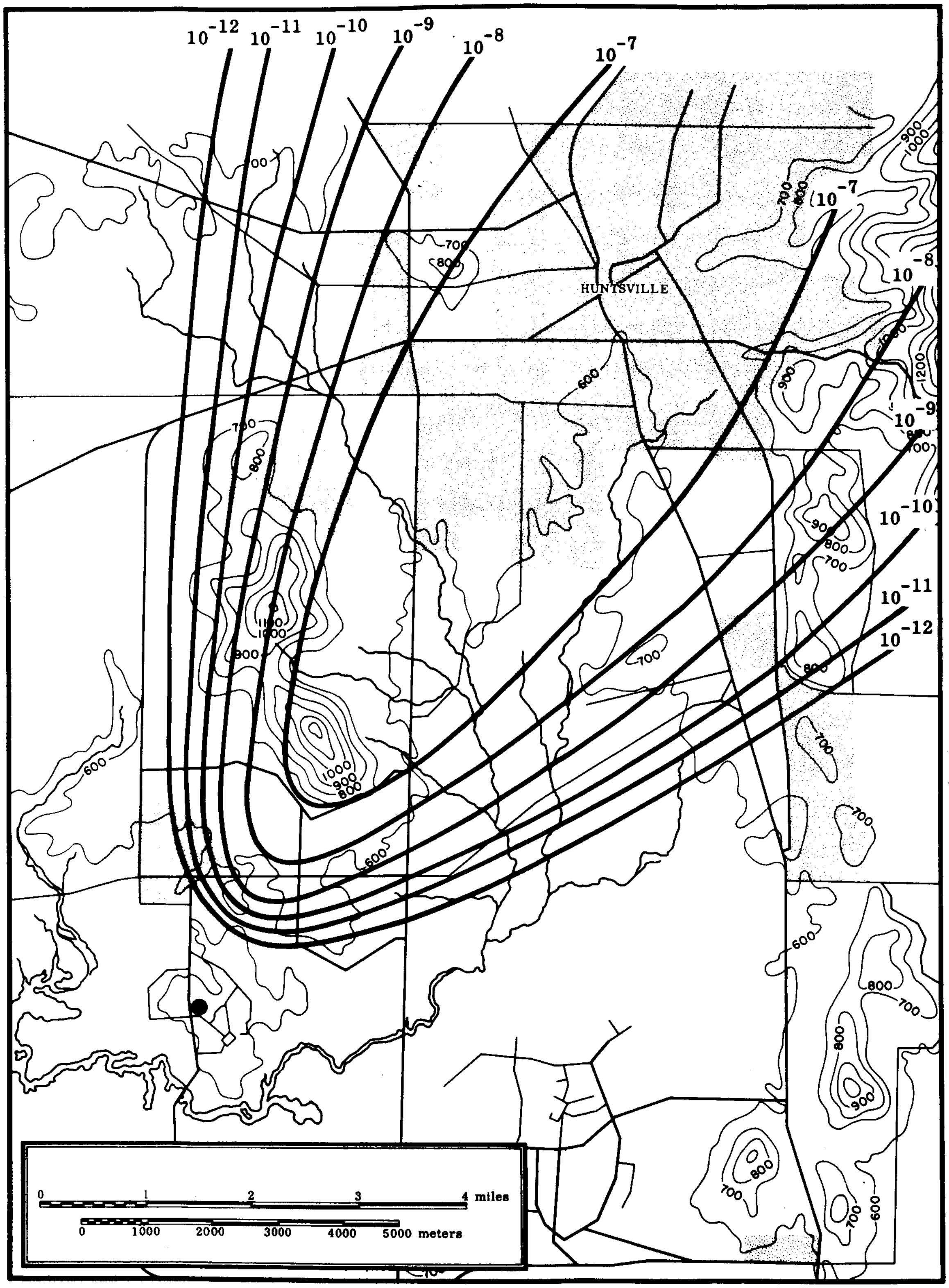

Fig. 1.9. Con't. (b) Vehicle B.

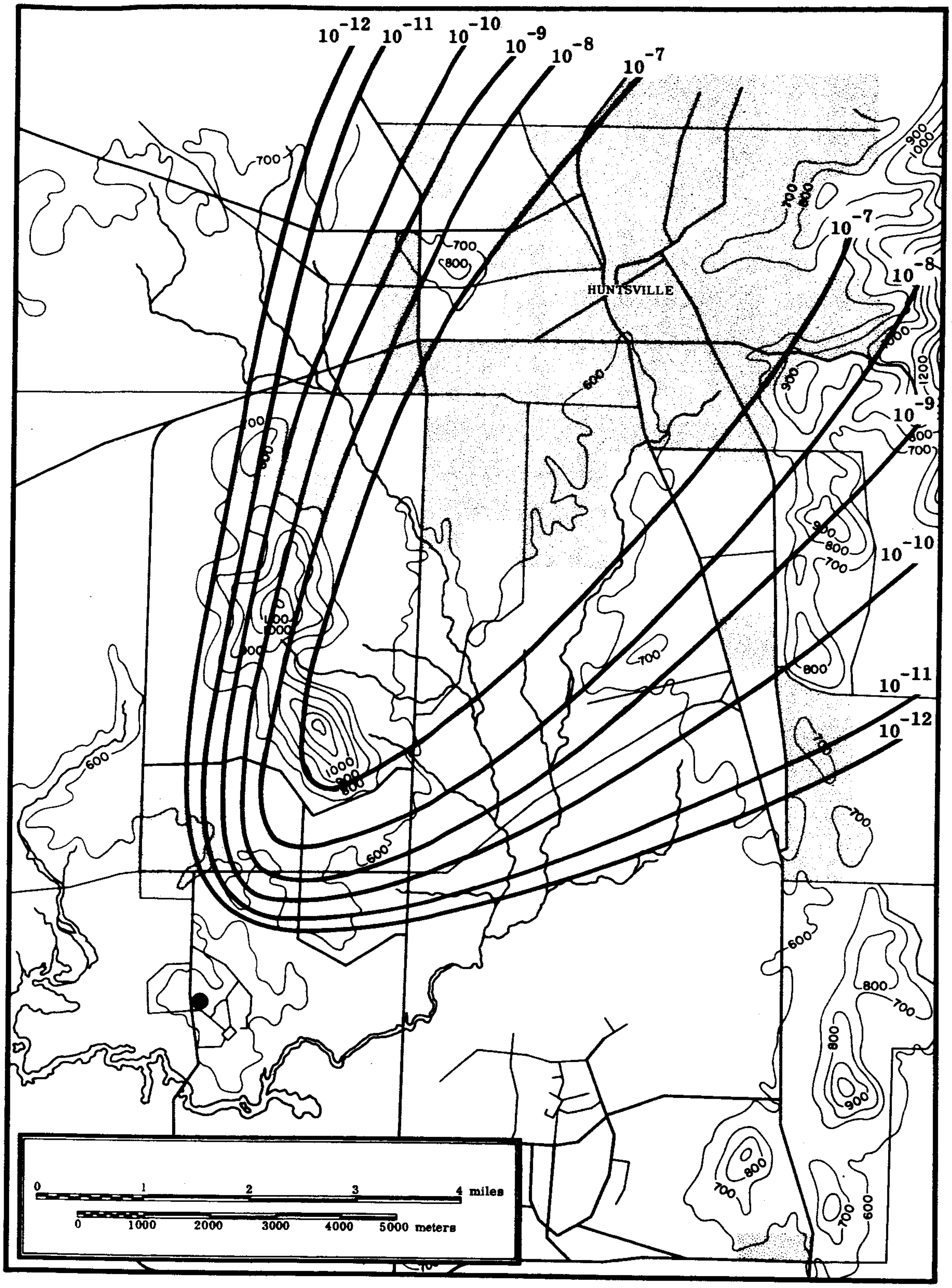

Fig. 1.9. Con't. (c) Vehicle C.

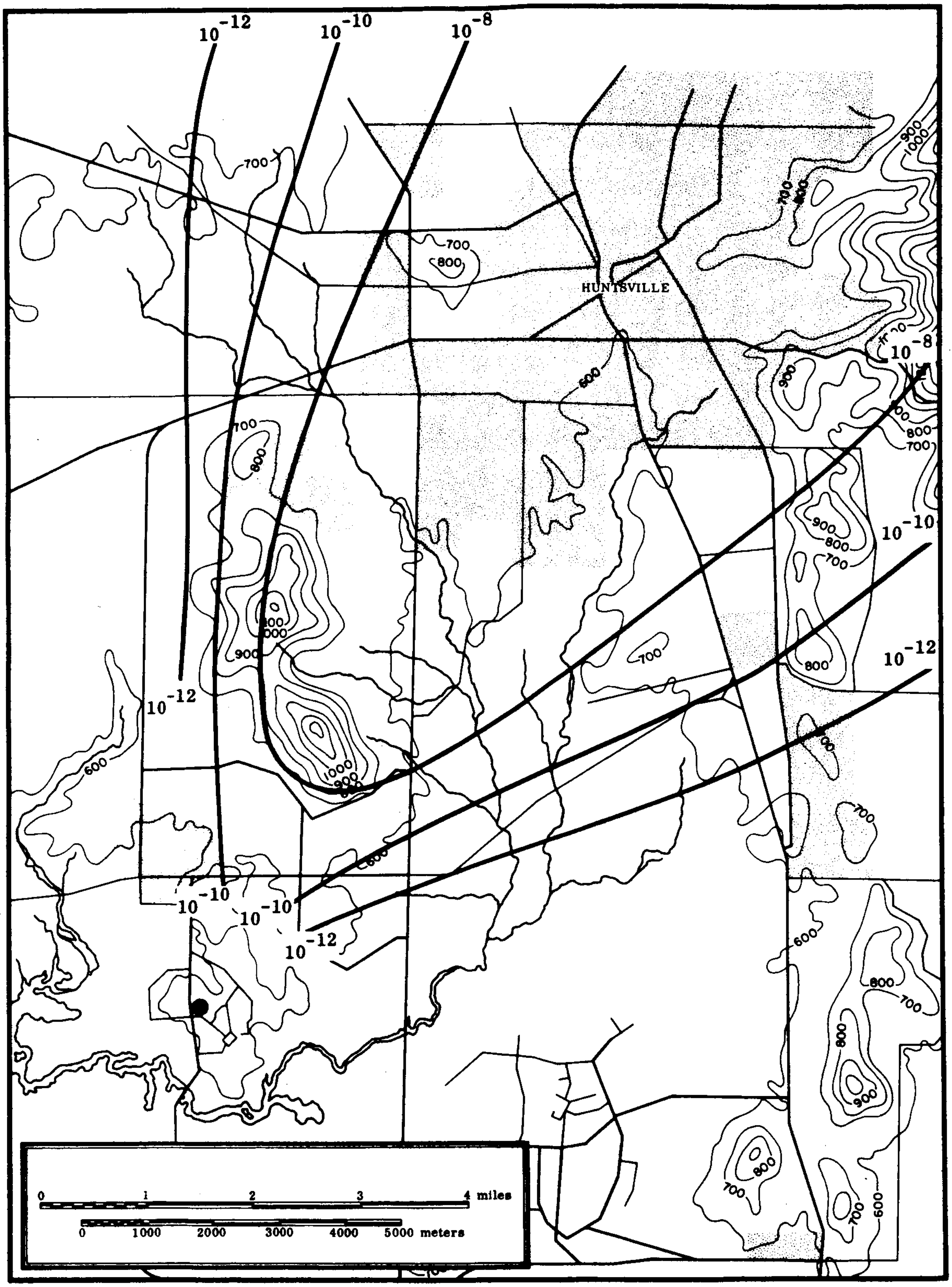

Fig. 1.9. Con't. (d) Vehicle D.

All total dosage curves in Fig. 1-10 possess maximum values at the source. Since these are dosages the magnitudes of the maxima are considerably larger than the peak concentrations illustrated previously for static firing tests. Near the source the centerline dosages were found to be relatively insensitive to reasonable variations in cloud growth and deposition rates. However, at greater distances from the source, the effects of deposition as modeled in this study increase in importance. No information is available on the magnitude of Λ that should be used for the gases of interest in this study. The values of Λ used in these calculations are typical of those listed by Pasquill [5], based on experiments with iodine—131 by Chamberlain and Chadwick.

Two examples of computed ground level total dosage patterns from LF spill sources are shown in Fig. 1-11. These figures serve to illustrate the effects of lateral cloud growth rates on the width of the dosage pattern.

1.3 Conclusions and Suggestions for Model Refinement

A preliminary mathematical model that attempts to describe the transport and growth of a gas or vapor cloud released from a quasi-instantaneous volume source in low-level shearing wind flow was formulated and programmed for use on a digital computer. Computations of smoothed peak concentrations and total dosages were performed for plane polar grid points within a 90 degree sector at ground level from the source to distances of about 15 km. The computations were performed for specified initial conditions believed to be representative of test firing exhaust releases of hydrogen fluoride and pipeline spill releases of liquid fluorine at Marshall Space Flight Center, Huntsville, Alabama. Estimates of concentrations and dosages due to normal launch exhaust releases, pipeline spills, and conflagrations were derived for Cape Kennedy and are

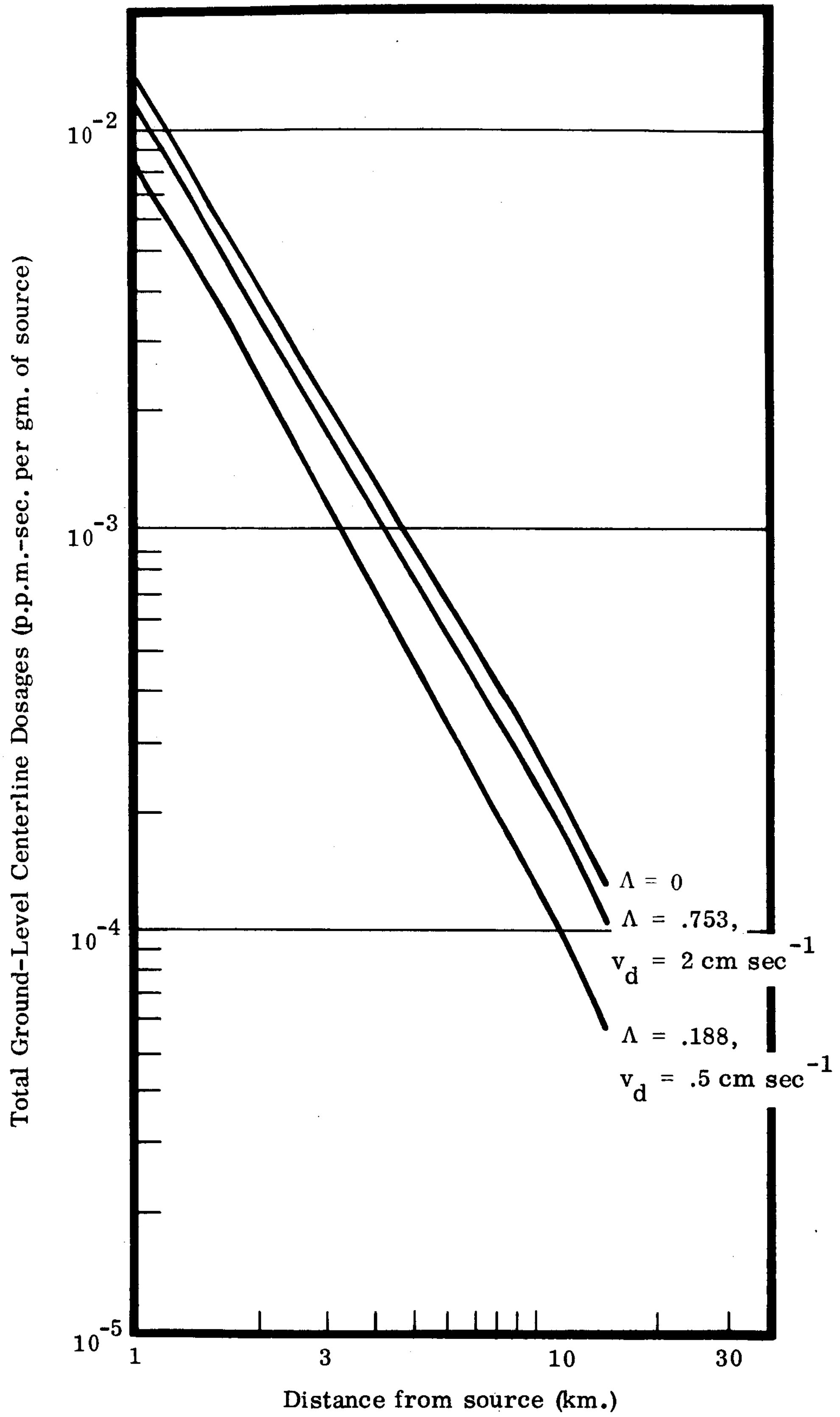

Fig. 1.10. Total centerline dosages at ground level as a function of distance from a LF spill source.

(a) Minimum dilution conditions.

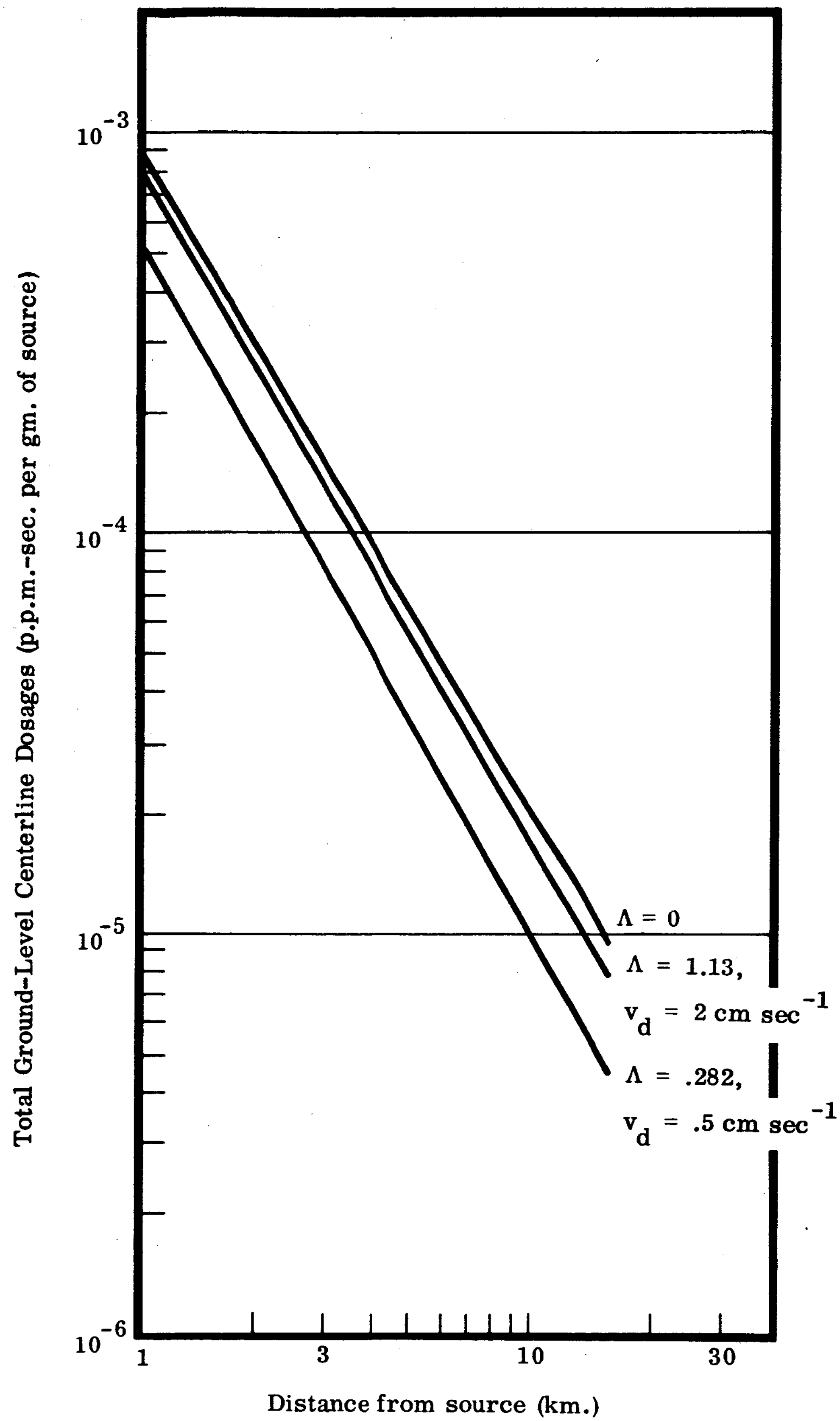

Fig. 1.10. Con't. (b) Maximum dilution conditions.

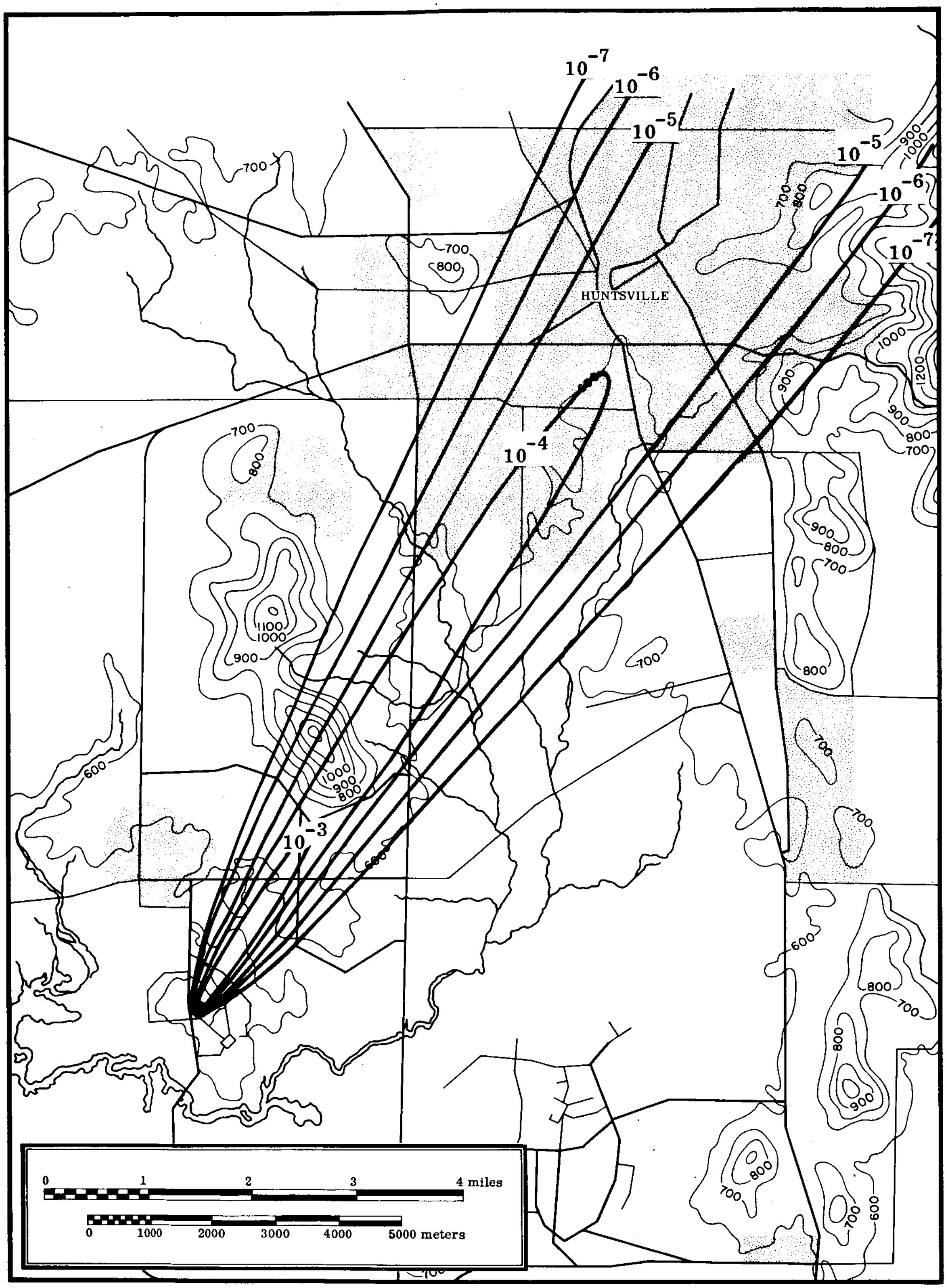

Fig. 1.11. Total dosages at ground level downwind from a LF spill source. Contours at intervals of 10 ppm-sec. per gm. of source.

(a) Minimum dilution conditions. Deposition constant $\Lambda = .753$ sec.$^{-1}$.

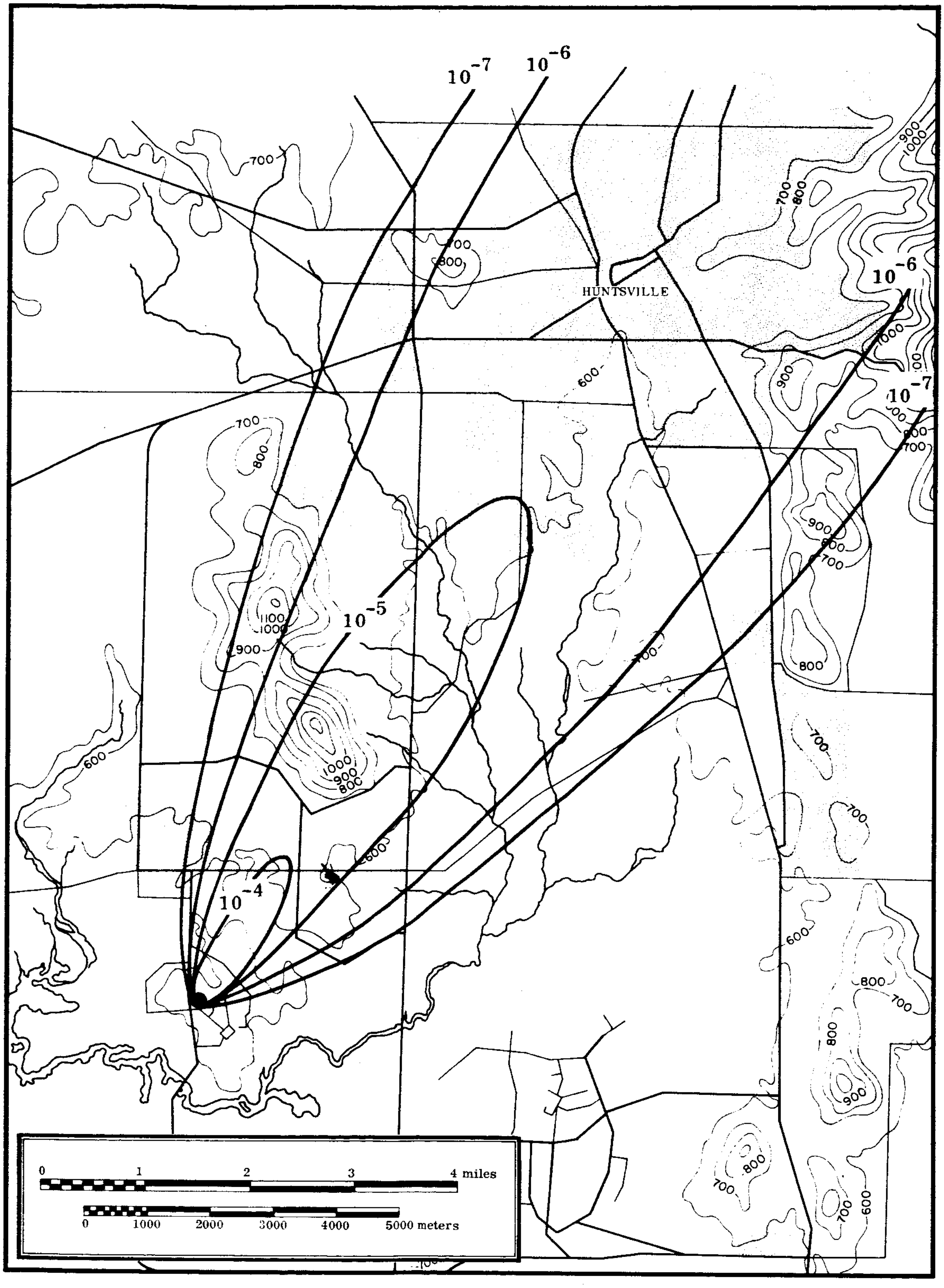

Fig. 1.11. Con't. (b) Maximum dilution conditions. Deposition constant $\Lambda = 1.13$ sec.$^{-1}$.

described in Volume 2 of this report.

The model has served to indicate roughly the magnitude and severity of the potential environmental exposure problem consequent to the use of certain toxic fuel additives. In addition it has been useful as a guide to the design of an experimental facility needed to support or negate the theoretical exposure estimates. Recommended and alternative designs for such a facility at MSFC are described in Part 2. At the same time it must be recognized that both the procedures used for modelling the various sources and the diffusion model have serious shortcomings and inadequacies. In some instances it has been possible to show that ground-level concentrations are sensitive to specific model assumptions; in others the sensitivity is unknown. For these reasons it is recommended that both the source phase and the diffusion phase be re-examined in an effort to formulate more realistic initial and boundary conditions and in an effort to provide a more faithful description of cloud dilution in the atmosphere near the ground.

In modelling a heated source cloud the effects of radiative cooling, formation of toroidal clouds, chimney or column convection effects of a sustained source, and entrainment of air accompanying the horizontal deflection of high momentum exhaust should be considered. Suitable photographs should be used when possible for quantitative information on the heights and dimensions of clouds. More information is needed on the total quantity of heat released, the volume and the molecular weights of gases emitted at the source. The behavior of unmixed or poorly mixed volumes of HF and F_2 under ambient temperatures should be investigated.

A more comprehensive and detailed survey of previous experimental studies is needed as a basis for improved estimates of σ_r, σ_Θ, and σ_z for quasi-instantaneous sources. Selective use of continuous source cloud measurements made under conditions of minimum low frequency wind direction changes should provide a firmer basis for modelling lateral cloud growth. Such measurements should be taken in such a way that vertical shear effects are not included. Experimental peak-to-average concentration ratios for various sampling times are needed to provide more realistic exposure estimates. The importance of these considerations cannot be overemphasized since both the use of continuous source cloud variances and the use of smoothed concentration distribution curves tend to underestimate the exposures that will be experienced at some ground-level locations.

Distortion of the gas cloud by systematic wind shear increases the area to volume ratio of the cloud. Since eddy diffusion takes place to a large extent across the interface between clean and polluted air, this will result in enhanced dilution rates that are not adequately accounted for in the model. A more thorough study of cloud distortion is needed too for improved modelling of the concentration distribution curves at ground level in and normal to the direction of the wind. The rough approximations used in this study are not valid for large wind shears or at large distances from the source.

The effects of vertical variations in σ_z and non-uniform vertical temperature gradients within the total exhaust cloud layer need investigation since both may have important consequences in terms of surface concentrations.

Topographically induced influences on cloud growth rates and on time and space variations in cloud transport are important considerations for specific sites. Finally, the effects of chemical reactions, washout by precipitation, and dry deposition on gas or vapor cloud diffusion patterns should be included in a systematic review of the problem.

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2.0 EXPERIMENTAL PROGRAM FOR MSFC

2.1 Introduction

The following sections delineate an experimental program to either verify or disprove the models used in calculations presented in Part 1 and Vol. II of the report and to provide observational estimates of the parameters required for calculations by actual measurement of concentrations in the geographic area of MSFC. Tracer techniques are recommended which are designed to be coupled to meteorological measurements to permit a description of the dilution capacity of the atmosphere. The experimental program is designed to yield models describing the diffusion process which may be used operationally with observed and forecast meteorological conditions.

Previous sections of this report have attempted to define the relative concentrations or dosages of toxic materials at points of interest to MSFC personnel using a basic statistical model of the diffusion processes involved and certain assumptions concerning the source configurations. Two sources were considered in the model, and the same are considered for the experimental program, i.e., a spill of toxic material without conflagration and the diffusion of exhaust gases from static firing tests. For purposes of the design of the program, it is assumed that spills of toxic material may take place at any time of the day or night and that the most critical situation is one where the spill occurs during stable atmospheric conditions associated with a nocturnal inversion. This is also a period of pronounced local effects on low level wind flow. While diffusion measuring field programs have been numerous, none have dealt with the problem of stably stratified flow to the distances of interest here except where the terrain involved was very uniform. The experimental program is designed to provide reliable concentration estimates at locations both on- and off-site under these conditions. Measurement of concentration resulting from surface releases under other stability conditions is appropriate with the network designed for the stable case.

Measurements of concentrations and resultant determinations of diffusion parameters for static firing tests are complicated by the source configuration. Exhaust gases are carried aloft by the buoyancy of the cloud as well as the blast deflector. Measurement of surface concentrations off-site may be carried out in the same way as the spill case, but the release of tracer material will have to approximate the release of exhaust gases to provide valid results. It is proposed that these tests be accomplished in conjunction with actual static firing tests at MSFC with the introduction of a suitable tracer into the exhaust from the rocket. Details of the tracer generation and sampling programs are discussed in succeeding sections.

The design of a network of surface sampling positions has been approached from the viewpoint that it should be both adequate to provide reliable scientific measurements and reasonable from the standpoint of cost.

Appendix A provides a discussion of how the sampling network should be designed to provide measurements of peak concentration within varying factors of the true peak at 90% confidence levels. The results of this analysis are included in the design configurations presented in the remainder of this section.

Three design configurations are presented; the first is required only to answer the question of the validity of the model used in the first part of the report; the second design goes a step farther, adding more sampling arcs and additional meteorological equipment to permit evaluation of the coefficients used in the model as well as the model; the final design adds more detail to the total picture permitting definition of new models, if required, and sufficient measurements to prepare forecasting techniques.

Succeeding sections will discuss site topography and geography, data requirements, facilities required, recommended test programs with schedules, data analysis and processing, and cost summaries of the three basic designs.

2.2 Site Description

Air flow, turbulence and atmospheric stability are all affected by the terrain in the layer at the surface of the ground. These items are the determining factors in diffusion of material in the atmosphere, therefore the design of an experimental program must take cognizance of the topography of the area. Other factors make it necessary to consider rural versus urban environments because of the effect on diffusion and, from the standpoint of logistics, roads, power, communications and property ownership must be considered.

2.2.1 Topography

The 10 by 8 mile region to the north and east of MSFC is characterized by a north-south ridge of hills rising 800 feet above the valley floor at a distance of 8 miles east of the test site. A north-south row of 300-ft hills 6 miles east of the test site provide a less complete barrier to air flow. In the northern portion of the reservation, Weeden and Madkin Mountains appear prominently 660 ft above the valley floor and only 3 to 4 miles from the assumed source location at the static test stand. Other terrain in the area of interest, i.e., Redstone Arsenal Reservation, Huntsville and suburban areas, is relatively flat, some of it marshy and partially covered with growths of trees to 40 ft.

2.2.2 Rural Versus Urban Environment

Huntsville, as an urban entity, occupies the north-central to northeast portion of the area of concern. Urban residential areas have expanded to areas adjacent to the boundary of the Military Reservation, e.g., West Huntsville, Westlawn and Pea Ridge. It is anticipated that enhanced mixing will occur in urban areas as opposed to rural areas because of increased roughness and temperature differences; however channeling by the valley may offset this advantage. It is not the purpose of the experimental program discussed below to measure the effect of the urban complex per se but to determine if concentrations are lower than would be anticipated by extrapolation from rural areas.

2.2.3 Property and Facilities

The objectives of the experimental program require measurements that are not on U.S. Government Property, particularly when concerned with concentrations that might be expected at Huntsville and surrounding urban residential areas. If the program is to provide sufficient measurements to be useful, it must be done with the consent and cooperation of the local government and populace.

Selection of sampling locations, while conforming to the network design in the next section, should be made with regard to public rights-of-way so far as possible and placed on private property only when absolutely necessary. The latter requirement is only one of cost consideration because of the time required for individual negotiations for permission to enter the property. Sampling positions have been suggested in the next section with regard for these considerations.

Sampling on the government controlled property is assumed to be with permission of the government. Effort will be made to avoid restricted areas in the planning stages unless they are areas of special interest so far as concentrations of contaminant are concerned.

In summary, the area of interest for this experimental program is assumed to be in the northeast quadrant centered on the static test stand in Test Area 9 extending to the hills on the east, and Huntsville in the northeast and north.

Depending on the source and complexity of the program, there may also be interest in concentrations up to five or ten thousand feet above the ground over this area. These items are covered more specifically in the next section on data requirements.

2.3 Data Requirements

Three test configurations are discussed as outlined in the introduction to the test program. Objectives of each configuration and data requirements to meet these objectives are presented below. The number of tests indicated are based on consideration of logistics and the climatological wind rose for Madison County Airport. Some refinement may be necessary to account for cases lost due to precipitation, fog and transient features that are not accounted for by long term climatological averages.

Surface sampler spacing is based on the analysis presented in Appendix A. The analysis was addressed to three design problems:

(1) To derive approximate representations of the error distributions of sample estimates of concentration parameters, as a function of separation between observations.

(2) To determine the maximum angular spacing that will assure, with 90% confidence, that the ratio of an actual to an estimated concentration parameter will not exceed a stated upper tolerance limit.

(3) To determine the greatest time interval between measurements that will assure, with 90% confidence, that the ratio of actual instantaneous peak concentration to estimated instantaneous peak concentration shall not exceed a stated upper tolerance limit.

Attention was centered on statistics related to three parameters:

(1) Integrated concentration: Ratio of estimated integral to actual integral because integrated concentration is the usual measurement obtained in sampling programs.

(2) Variance of concentration: Ratio of estimated variance to actual variance because these parameters are controlling in the statistical diffusion model being evaluated.

(3) Peak concentration: Ratio of actual peak concentration to estimated

peak concentration because of the importance in setting standards of exposure based on peak-to-mean ratios and short-period peak exposures.

Specifications for angular spacing and time spacing between observations at a given downwind position have been determined to assure that the ratio of the actual peak concentration to the estimated (from observations) peak concentrations is less than or equal to two with 90% confidence. Angular spacing requirements were based on values of σ_y (lateral standard deviation of concentration distribution) considered appropriate for a surface release in moderately stable conditions. Time spacing requirements were determined by assuming the localized distribution of concentration in the X direction is the same as that in the y direction over relatively small distances and that the cloud moves uniformly with speed $\bar{u}$. Thus if distance $X = \bar{u}t$, specifications are determined for a sufficiently accurate network as outlined in Table 2.1. Complete specifications may be found in Appendix A.

Table 2.1

Specifications for Angular Space and Time Spacing to Assure Peak Concentrations Are Estimated Within a Factor of 2 With 90% Confidence. ($\bar{u}$ assumed 3 m/sec.)

X (km)	σ_y (Meters)	Angle (Degrees)	Time (Min.)
1	68	7.8	0.76
5	275	6.3	3.06
10	500	5.7	5.56
15	710	5.4	7.96

Note that the spacing values given in Table 2.1 are twice the standard deviation assumed for the crosswind concentration. One further assumption regarding measurements of dosage was that measured values did not differ by more than 15% from true values.

With the preceding background, three test designs are presented which will accomplish three increasingly comprehensive objectives.

2.3.1 Test Program A

Objective—To verify predictions of peak concentrations and total dosage made with the model in part 1 of this report.

The tracer sampling network will consist of four arcs, referring to Fig. 2.1; these are recommended to be at 1 and 3 km over 120 degrees from the source and the arc starting east of Gate 3 at Mathis Mountain, extending just south of Madison County Airport and ending against Weeden Mountain and the arc through downtown Huntsville just north of Route 431 and 72. Spacing will be in accordance with Table 2.1. Surface samplers are recommended to be rotorods with three sequential samplers on each arc to give the time resolution needed to determine peak concentrations. The network is designed to accomodate both simulated spill and static firing sources.

Meteorological measurements are assumed to be those already available at Huntsville including rawinsonde observations taken in conjunction with the test, with the addition of two anemometers to aid in wind flow determinations located,(see Fig. 2.1), on Martin Road near the reservation boundary and two miles northwest of the Madison County Airport. In this design configuration these are assumed to be surface units on a hinge-guyed tower at a height of 70 feet to obtain information above the tree and urban housing levels. Strip chart recording is recommended, and it is assumed the equipment will be operated continuously so as to obtain a climatology of wind flow.

Number of tests shall be as many as possible with wind conditions that are specified, i.e., flow toward Huntsville. Two operating periods of four months each are recommended throughout the test plan. In this configuration it is recommended that at least 20 spill tests and 5 static firing tests be obtained in each four-month operational period. Spill tests will be scheduled

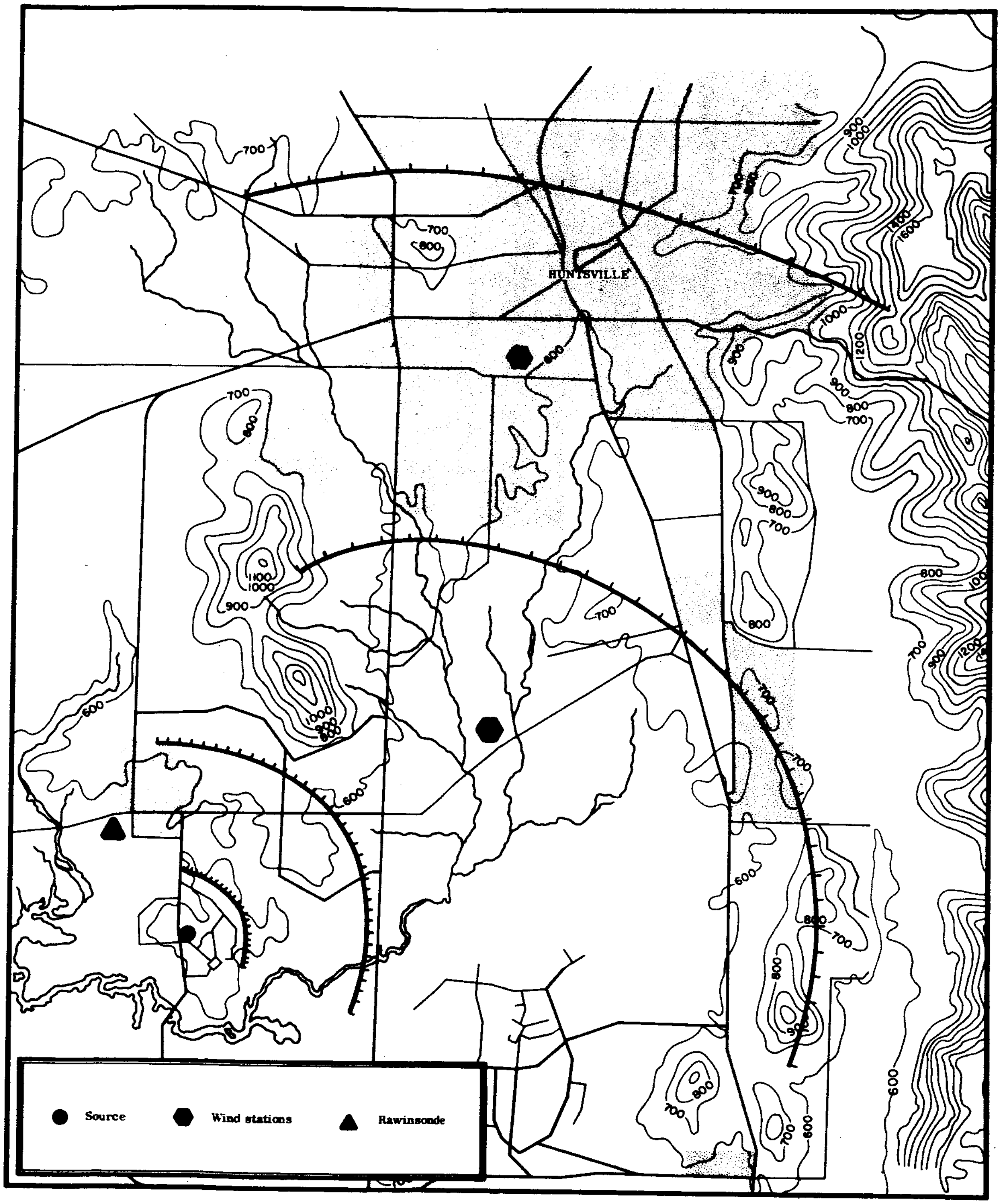

Fig. 2.1 Meteorological and tracer sampling position for Plan A.

to cover all atmospheric stability situations and times of day of interest to the sponsor.

In summary the following data requirements are to be met.

(1) 40 spill tests under various conditions.

(2) 10 static firing tests under usual static firing meteorological conditions.

(3) All meteorological observations regularly available at MSFC plus extra rawinsonde observations and two additional surface wind anemometer locations

(4) Four surface tracer sampling arcs containing a total of 12 sequential tape samplers and 76 rotorod sampling positions distributed with 15 on arc 1, 20 on arc 2, 23 on arc 3 and 18 on arc 4.

2.3.2 Test Program B

Objective—To verify predictions of peak concentrations and total dosage made with the model in part 1 and to verify the horizontal diffusion coefficients and infer the validity of the estimated vertical diffusion coefficients.

The tracer sampling network includes all locations listed under Plan A and two arcs are added, see Fig. 2.2, from Madkin Mountain southeast to Redstone Road and the arc circling north of the airport in the outskirts of Huntsville. It is further recommended that sampler spacing be doubled on the three outer arcs and increased by 50% on the three inner arcs to permit testing in more stable atmospheric conditions with a greater chance of success. Once again the network is designed to accommodate both spill and static sources.

Surface wind and temperature measurements, including air flow and turbulence, are required in conjunction with the tracer measurements if an understanding of the relation between these variables and diffusion is to be attained. The terrain around MSFC is a major factor affecting local low level

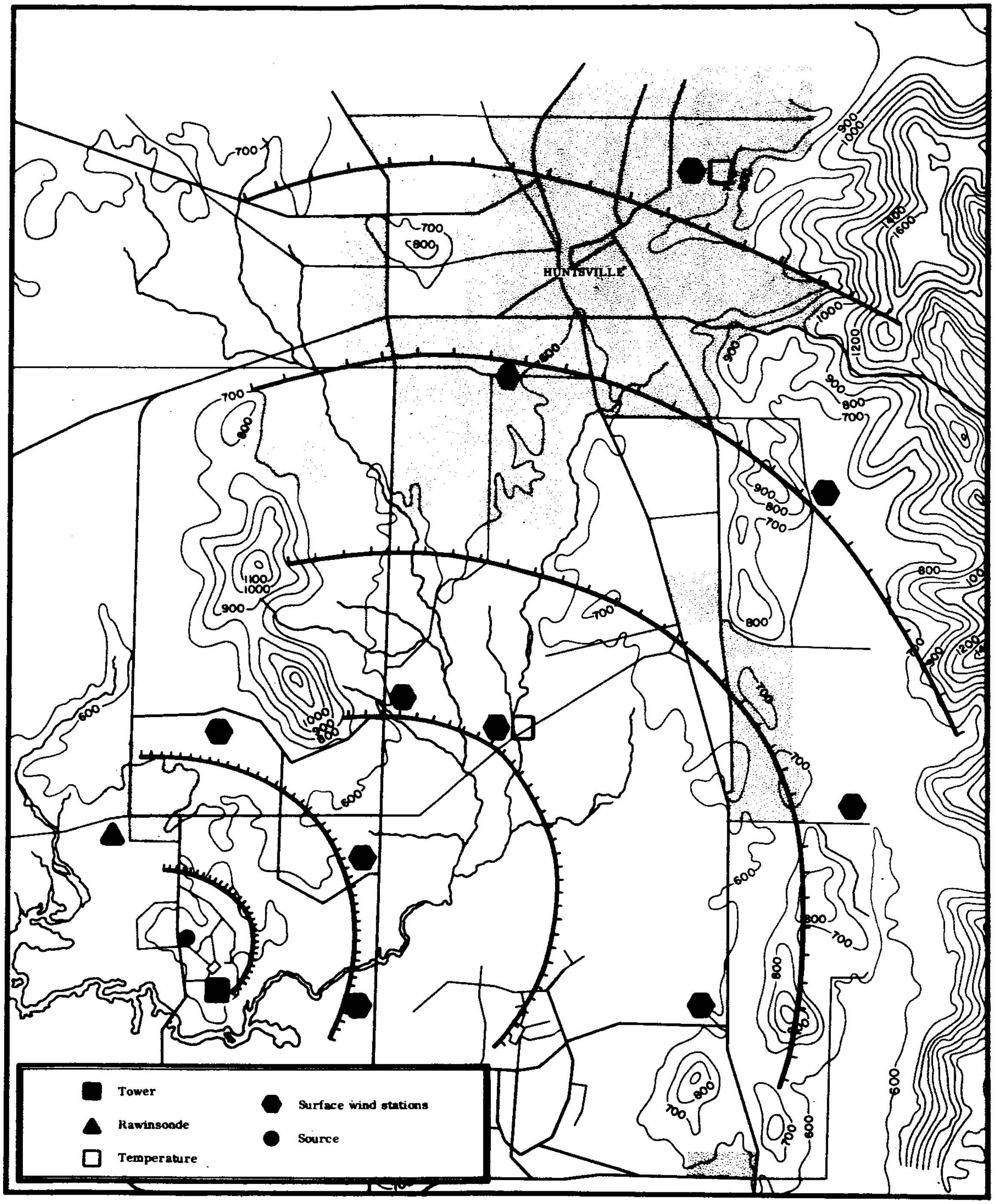

Fig. 2.2 Meteorological and tracer sampling position for Plan B.

flow and the design of a surface observing network (both tracer and wind) must account for it if a realistic prediction program is to be developed. It is recommended that wind speed and direction be measured at ten well-located sites around the valley to define the near-surface wind flow pattern and, indirectly, the trajectory of a low-level airborne aerosol cloud. Three temperature measuring sites are suggested, at the source, on Martin Road at the site boundary and in an urban location in Huntsville.

In addition to the flow measurements, it is proposed that a 300 ft tower be erected near the source with tri-axis measuring anemometers at three levels to provide turbulence information. The measurements should be made at 75, 150 and 300 ft; temperature measurements would also be desirable at these positions. Turbulence measurements from the source would be expected to be closely related to diffusion taking place in the first few kilometers of travel for spill sources, thus it should provide an eventual predictive method for on-site concentrations resulting from spills.

It is also assumed that existing MSFC facilities, particularly the rawinsonde will be used to bolster the observing network described above.

Number of tests are expected to be 14 spill and 5 static firing tests during each four month operational period covering various meteorological conditions as outlined under Plan A. The total number of spill tests is reduced because of the increased data obtained under this plan.

In summary, the following data requirements are to be met.

(1) 28 spill tests under various conditions.

(2) 10 static firing tests under usual static firing conditions.

(3) All meteorological observations regularly available at MSFC with additional rawinsonde flights for tests.

(4) Data from 10 stations measuring surface air flow and three temperature measuring locations.

(5) Turbulence data from 3 levels on a 300 ft tower near the source.

(6) Six surface tracer sampling arcs containing a total of 18 sequential tape samplers and 181 rotorod sampling positions distributed with 22 on arc 1, 30 on arc 2, 33 on arc 3, 46 on arc 4, 30 on arc 5 and 20 on arc 6.

2.3.3 Test Program C

Objective—To verify predictions of peak concentrations and total dosage made with the model in part 1, verify horizontal and vertical diffusion coefficients and develop comprehensive diffusion prediction techniques.

The surface tracer sampling network is expanded to seven arcs following a trajectory towards Huntsville with additional samplers on the west side of Weeden and Madkin Mountains to pick up split clouds if these occur, (see Fig. 2-3). Density of samplers is doubled at all arcs over the recommended spacing in Table 2 of Appendix A. This is done to permit more stable atmospheric conditions to be measured and to improve knowledge of the crosswind distributions on each arc. Three sequential tape samplers are required on each arc to provide time histories of concentrations in the downwind travel of the cloud.

Vertical sampling by two methods is proposed for this configuration. Tethered balloons, to be used as a support for vertical sampling arrays, are proposed for ground source experiments within 3000 meters of the release point. A portable tower within 100 meters of the source is also proposed as an aid to source configuration definition for spill cases. Aircraft sampling is the only reasonable method to perform vertical sampling at moderately large distances for ground sources and all distances for static firing tests. Two aircraft equipped with special sampling equipment are suggested, or definition will be insufficient to make sampling worthwhile. Sampling is proposed at positions over Huntsville and halfway from the source to Huntsville with extra

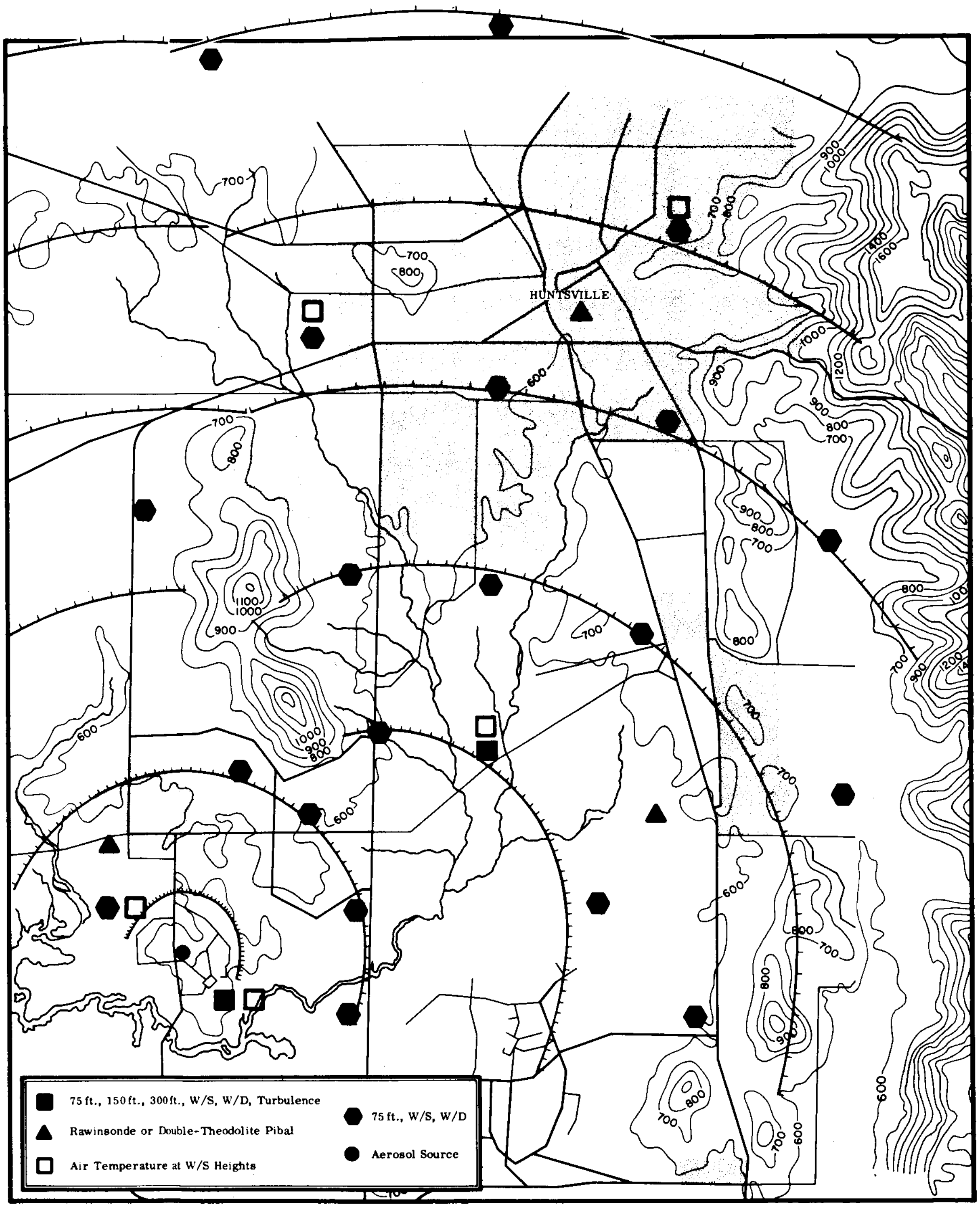

Fig. 2.3 Meteorological and tracer sampling positions for Plan C.

vertical samples taken close to the source for static tests to provide source definition.

Wind and temperature sampling positions are also indicated in Fig. 2.3. A network of 22 surface wind stations are proposed to measure flow in the valley, five of these have temperature measuring equipment. Two towers of 300 ft each with three levels of turbulence sensing tri-axis anemometers are proposed, one near the source as in Plan B and a second on Martin Road near the site boundary to measure turbulence in the flow toward Huntsville.

Use of the MSFC rawinsonde is assumed for this plan also with two contractor operated double theodolite pilot balloon observing sites added as indicated on Fig. 2.3 to provide information on free air flow in the valley.

Number of tests are recommended to be 12 spill tests and 5 static firing tests during each four month operational period. The number is reduced from Plan A and B because the increased complexity of the operational network will provide enough additional information to reduce the required number of tests.

In summary, the following data requirements are to be met.

(1) 24 spill tests under various meteorological conditions.

(2) 10 static firing tests under usual static firing conditions.

(3) All meteorological observations regularly available at MSFC with additional rawinsonde flights for tests.

(4) Data from 22 stations measuring surface air flow and five temperature measuring locations.

(5) Turbulence data from 3 levels on each of two 300 ft towers, one near the source, one in the valley.

(6) Double theodolite pilot balloon observations at two locations.

(7) Seven surface sampling arcs containing a total of 260 rotorod sampling positions as indicated in Fig. 2.3 and 21 sequential tape sampler positions.

(8) Vertical samples at 5 ft intervals from a portable tower near the

source and at 50 ft intervals up to 450 ft on each of four tethered balloons at about 3000 meters from the source.

(9) Vertical concentration samples gathered by two specially equipped aircraft to provide vertical definition above the balloon sampling heights and at greater distances.

2.4 Experimental Equipment and Facilities

The following sections discuss equipment, supplies and facilities required to conduct tests outlined in Section 2.3. Items are discussed on an individual basis where possible and as part of a system where a system is necessary. Costs are presented for some individual items for comparative purposes, but costs for each Design Plan are contained in Section 2.7.

2.4.1 Tracer Selection

A tracer technique was sought which would permit similar tracer materials and, in the interest of economy, the same collection devices to be used for the investigation of both spill and test firing situations. A tracer was also wanted which was non-toxic and non-objectionable in other ways, at least in the quantities in which it will be discharged to the atmosphere.

In order to be used in static test-firing, the tracer material must be stable at temperatures of approximately 5000°F if it is to be incorporated in the fuel or injected directly into the exhaust flame at the point of origin. This immediately rules out fluorescent pigment, organic dyes, and most non-toxic gases, although sulfur hexafluoride (SF_6), which can be detected by "electron capture" analytical techniques in concentrations as low as one part per billion (1 ppb), could possibly be used at temperatures up to 4000°F.

In order to use the same collection apparatus and analysis techniques, the tracers used for the spill and firing cases should both be particulates, or both be gases.

A summary of possible tracers is shown in the following table.

Tracer	Stable at High Temperature	Toxic	Remarks
Fluorescent Pigments (Zinc sulphide, or zinc cadmium sulphide)	No	No	Individual particles (3-4) easily and economically collected by rotorod samplers or filtration. Analytical technique well proven in field use.
Organic Dyes (Fluorescein)	No	Slight	Analysis more expensive than fluorescent pigment.
SF_6 (Gas)	Up to 4000°F	No	Detectable in concentrations of 1 ppb by "electron capture" analysis, but results not always reproducible.
Rare Earth Metals (Dysprosium, europium, indium, iridium, gold)	Yes	No	Detectable in amounts as low as 5×10^{-12} grams by neutron activation analysis, but analysis is expensive.

After reviewing the possible candidates, and considering the economics of the situation, it is recommended that particulates be used as tracers—fluorescent pigment for the spill case and rare earth metals for the static firing situation. Initial planning is based on rotorod samplers being used as collectors for both the fluorescent pigment (FP) and the rare earth metals.

Some development work will be required in connection with the neutron activation analysis. Background interference, both from airborne dust particles which may be present at the test site, and from the grease used to coat the rotorod samplers must be determined. Estimated cost to make these determinations, which will also yield information as to the sensitivity of the analysis and quantity of tracer required, is $200.00 for each of five (5) possible tracers. Costs for consultations are included in Section 2.7 to consider methods of tracer selection and dispensing. For example, if fluorescent pigments could be introduced into the jet plume at a distance where the temperature has dropped to satisfactory levels, this tracer may be more feasible. Estimated sensitivity (barring background activity) of the candidates are:

Element	Instrumental Sensitivity (μ g)
Au	0.0005
Dy	0.000005
Eu	0.0005
In	0.0001
Ir	0.001

Additional development work will be required to design a mechanism for injecting the material into the rocket flame at its source if the tracer cannot be mixed with the fuel.

While it is anticipated that rotorods will be satisfactory for collection of samples of rare earths, feasibility tests at the start of the program may indicate the need for a filter type sampler. It is understood that the U.S. Air Force is currently using neutron activation analysis on tracer materials collected by airborne filtering devices. A "need to know" should be established to take advantage of their experience in this field and avoid duplication of effort.

2.4.2 Aerosol Generation

Fluorescent particles are considered the best tracer available for spill tests because of the sensitivity of the method and the availability of a relatively inexpensive and portable sampling system. Generators or dispensers of fluorescent particles are inherently more expensive than generators of other aerosols such as gases, but this expense is more than outweighed by savings in cost of sampling equipment and analysis in the FP technique.

Particulate aerosols may be generated by a dry powder dispenser such as the Metronics Model 5 and associated control equipment. These may also be generated by dispensing a particulate slurry in a fine fog. The Todd Insecticide Fog Applicator has been used extensively for this purpose. Costs in the summary have been based on a dry dispenser using prepared and calibrated fluorescent powder.

Generation of particles for sampling of static firing tests is a much more difficult problem. If rare earths are used, they could be introduced by adding them to the fuel or introducing them into the plume at the blast deflector. If fluorescent particles are used they would have to be added at a point where the plume temperature drops to 1000°F. One suggested method is fogging with a fire hose nozzle while another is dumping dry particles from an aircraft or helicopter. Both methods present some major engineering difficulties. Simulation of static firing sources is not judged satisfactory because the buoyancy of the plume is very important to subsequent surface concentrations of material in the distances of interest.

2.4.3 Tracer Sampling—Surface

It is recommended that rotorod samplers be used to sample the fluorescent particles. Pricing is based on the purchase of the basic rotorod sampler and providing each with a small control and battery box. The controls required are simply on-off and a timed switch to reverse the rotation of the rotorod. The box would have a variety of mounting techniques to suit all installations.

At three points on each sampling line the program calls for incremental samples to define the shape of the aerosol cloud at the surface. Allowance has been made for 24 sequential samplers of the continuous tape type (Gelman Instrument Company) and for provision of suitable power at remote sites.

To determine the characteristics of the aerosol cloud very close to its source, a small, portable, tower is needed to mount rotorod samplers to a height of 50-70 feet. The tower would only have to stand during winds acceptable for an experiment. Such a tower can be fabricated from standard lines of self-supporting towers, a large but light-weight base, with small wheels attached to the base in such a way that the tower can be rolled into position when horizontal and then upended and sandbagged for use once the samplers have been placed. The cost of a tower system built to these specifications is $300.

To sample any aerosol cloud that passes through the 300-ft downwind tower, rotorod samplers can be placed on a light pulley assembly to run up the face of the tower or up a guy line. An allowance for fittings has been made.

Rotorods have been used successfully for balloon sampling procedures and are recommended for such installation. A different battery box is required to reduce weight, but costs are the same.

It is assumed that if rare earth tracers are used that rotorod collection will be satisfactory; if this is not the case filter type sampling equipment will be required at significant increases in cost of the sampling program.

2.4.4 Tracer Sampling—Aircraft

A major purpose in carrying out static test aerosol diffusion studies is to determine the history of an aerosol cloud aloft after its violent generation. To do this the cloud must be sampled adequately to determine its distribution in space at several different times. The only approach thought feasible is through sampling from an aircraft. On investigating the current known position in this field of measurement, it became apparent that the continuous and rapid sampling of aerosol from an aircraft is a difficult and exacting task.

The instrumentation/aircraft must be a tried and proven package and the crew must be experienced in this type of work. These requirements become even more pronounced when one considers the critical aspect of the contribution of success in sampling to the success of the larger entity of a rarely available experiment.

The use of two L-19 GFE aircraft is proposed with the contractor providing a highly qualified pilot-technician to supervise the operation and to operate one aircraft. The second aircraft would be operated by a specifically selected and trained locally based commercial pilot or a GFE pilot. Samples of non-fluorescent particulates could be taken with a drum-type impaction sampler or of fluorescent particulates with a Hanford style real-time concentration recorder backed up by a drum-type sampler for integrated samples. The Hanford concentration recorder could be used directly for this requirement, but better results may be easier to obtain if the instrument were developed further. Thus the cost of aerial sampling will vary with the characteristics of instrumentation and aerosol as well as with the basic scientific requirements. An alternate approach is to contract for the sampling service with an organization equipped with suitable aircraft and personnel. An estimate of $55,000 for this function is based on properly instrumented aircraft of the Apache class, with the subcontractor maintaining one aircraft and pilot-technician-supervisor on site during active experimental periods. A second aircraft and operator would be on-call locally to fly a second sampling system under the direction of the pilot-technician.

Other approaches, generally involving the use of chartered aircraft during each individual experiment, promise many difficulties in program scheduling and flexibility, and in questions of measurement validity.

2.4.5 Balloon System

The balloon system is designed to measure the initial vertical distribution of the particulates in the formative stages of the plume. Samples should be taken at 50 ft intervals from the surface to 450 ft some 3 km downstream from the simulated spill source. At least two such vertical profiles are required to permit statistical significance, and the vertical profiles should be measured within 2 standard deviations of crosswind concentration or approximately 1000 ft in the crosswind direction. Therefore, to adequately cover wind flows from the southwest quadrant, some 15 vertical sampling sites are possible over the arc of radius 3 km from the source.

The only practical method for obtaining the vertical samples is to employ a flexible and completely self-contained balloon system. Blimp shaped tethered balloons have been employed for obtaining similar measurements in the past and should be readily adaptable to the unique needs of the Huntsville experiments. TRC suggests a 2000 cubic ft balloon, approximately 37 ft long and 11.5 ft in diameter. The balloon should be constructed from a heavy balloon fabric, such as neoprene coated nylon, to permit re-use for up to 15 flights. Such a balloon, when filled with helium, would provide the capability of carrying a 45 pound pay-load to 450 ft which is adequate to meet the experimental requirements.

The prime pay-load would consist of 9 rotorod samplers. In addition, upper and lower balloon strobe lights and two tetherline warning lights will be required to meet the Federal Aviation Agency requirements for night operations. To save approximately 10 pounds in the pay-load, it is suggested that the power for operating the lights be provided by a power cable from the ground rather than by airborne battery units. The lights, rotobar samplers, tetherline and power cable for a balloon at a 450 ft altitude will weigh about 43 pounds based upon experience with similar experiments.

To permit a reasonable probability of obtaining two such vertical samples of the aerosols within a lateral distance of 1000 ft, it is believed that a minimum of four such balloon systems must be employed. Four such systems will provide coverage over 3000 feet, or an 18 degree arc, which will be necessary to compensate for the short-term wind variability, particularly with the light winds usually encountered with a stable atmosphere. Further investigation of the actual short-term wind variability at the site will be required to assure that four balloon systems will be adequate. Additional flexibility to meet the larger scale wind variations can be obtained by varying the balloon launch sites on a day to day basis depending on the specific directions anticipated. Some fifteen sites should be prepared every 1000 ft along the sampling arc (radius 3 km). With the flexible system proposed, a balloon could be re-located to another site within one hour.

The balloon system recommended consists of the pre-inflated balloon attached to a specifically designed four wheel wagon. Built into the wagon is a gasoline powered capstan or winch, the necessary dry cell batteries and switches required for the power for the lights, the power cable, and the tetherline. The wagon should be designed to be towed by a standard vehicle, sedan or pick-up. Operationally it is envisioned that the balloon wagon would be stored in an available government furnished hangar (40 ft long x 14 ft wide x 20 ft high) and towed to the site selected for a particular experiment.

2.4.6 Surface Wind and Temperature Systems

An anemometer system should have a low threshold starting speed (preferably under 1 mph), good resolution and accuracy at low wind speeds (1 to 5 mph), and good reliability in continuous use. Fine time resolution of flow is not required. The main requirement for a temperature measurement system is that it have a reasonable accuracy in measurement and exposure (1 to 2°F) and need little maintenance.

A low threshold of wind speed will be obtained only with a sensitive anemometer system and rules out the more rugged and reliable systems such as the Aerovane. Available for selection are systems such as the Climet CI-3 or CI-9, the Beckman and Whitley model 50 or WS101, the MRI Velocity Vane. Current prices for these systems, with signal conditioners but without recorders, range as follows:

B & W Model 50	$4,925
Model WS101	1,640
Climet Model CI-3	1,322
Model CI-9	2,872
MRI Velocity Vane	1,395
with Vectorsyn	1,540

The Climet model CI-9 is a digital read-out system and the price includes its recording function. Its sensors are the same as the CI-3 model. The B & W model 50 has a capacitive direction transducer and the MRI Velocity Vane has an optional Vectorsyn direction transducer. Remaining systems use potentiometers as direction transducers. It seems, then, that the cost of sensitive wind-speed and -direction measurement systems, without recorders, is in the range of $1322 to $1640, and that a reasonable budget estimate would be $1600.

Graphic recorders usually supplied with wind systems are of the d'Arsonval-type, a common example being the Esterline-Angus Graphic Recorder. Prices of recorders recommended for use in these systems lie in the range of $1000 to $1200. Recorders would best be power-line operated for time synchronism of records and be capable of operation for lengthy periods without attention. Full scale wind-speed readings should be limited to 30 mph or less, to obtain reasonable resolution and accuracy at windspeeds of 1 to 5 mph. For maximum accuracy, recorders should be subject to a "dither" current to reduce the effects of pen stiction.

A moderately accurate survey of air temperature can be made, at some inconvenience but at low cost, by good quality mechanical thermographs in standard meteorological instrument shelters. A shelter/thermograph combination costs $320 plus installation. The main disadvantages of this proposal is that the instrument (a one-day chart is assumed for reasons of time definition) would have to be serviced the day of an experiment and that, without daily servicing, continuous records would not be available for general studies. For these reasons an electrical method of temperature measurement and recording is suggested.

A resistive thermometer and potentiometric strip-chart recorder cost about $100 and $850 respectively. No interface equipment is needed. The thermometer element must be aspirated and shielded against radiation at a cost ranging from $275 to $350 for a motor aspirated shield. A possible alternative is the Climet vane aspirated shield at $90, which should be more than adequate for experiment conditions but not for a full micro-climatology study.

The measurement of airflow for trajectory calculations critically depends upon the placement of the sensors. Considering the usual height of interfering structures and trees in the Huntsville area to be 30 to 40 ft, it is suggested that an anemometric level between 50 and 75 ft be considered for the general installation. For budget purposes a tower of 70 ft will be assumed.

A tower must be of a pattern that permits easy instrument access and maintains good azimuth reference. Fixed or telescoping multiple-guyed posts of the TV-trade are not deemed suitable Non-guyed utility poles, with steps and safety hoop, may have application where guys are objectionable but installed prices are as high as for inherently more desirable tower types.

Fixed, guyed, lattice towers or self-supporting lattice towers also must be climbed for instrument maintenance and may also be objectionable because of requirement for guys or extensive bases. Lattice towers may be purchased in telescoping or folding designs, but these usually involve guying arrangements. It is thought that tower selection would be conditional upon the specific site and that an estimate of cost would be based on a hinge-guyed fold-over tower to 70 ft, with its probable cost of installation and eventual removal and site restoration.

Allowances are listed for instrument cables for the run down the tower and horizontally to a recorder location, for outdoor protection of recorders, for power installation and for easement rights. These costs will vary from site to site and an attempt has only been made to list an average value.

A major variation in this plan is available with the use of the Climet CI-9 digital system. The sensors are the same, the overall cost is very close to the same, but the output is in the form of punched paper tape instead of graphic records. The punched paper tape is not in a directly computer-compatible form and must be converted to a suitable medium before automatic analysis. The basic punch is a mechanism produced by Fischer and Porter and is used extensively by the Federal and State governments for meteorological, geological, hydrographic, and traffic control studies. Conversion is available as a service by Fischer and Porter or a converter, at a cost of $6500, can be used to operate a leased IBM key punch. It is visualized that a digital system would output ten-second averages of wind speed, wind direction, and, if present, air temperature, every two minutes (or 5, 10, 15, 30 minutes). A fuller investigation would have to be made to ensure that adequate digital definition of the variables over the ranges required would be obtained. Because of potential savings in the data reduction phase, a digital recording system should be seriously considered.

2.4.7 Wind and Temperature Measurements to 300 ft.

Instrumentation for wind speed, wind direction and temperature recording has been discussed under surface measurements. A digital recording system could be made common to the three groups of instruments on a tower and it would then be economical to procure a system that outputs data directly on computer-compatible tape. Total cost of such a system would be marginally less than one employing graphic recorders.

Wind measurements for diffusion parameters may be obtained from suitable sensors such as tri-axis anemovanes, either by direct, on-line, computation and recording of an individual parameter or by recording the sensor outputs in a high-fidelity medium and the subsequent calculation of the various parameters from the record. The latter approach has the advantage of retaining the original sensor signals for any type of analysis later conceived.

There are three degrees of cost and complexity available in the approach to the requirement. If a measure of the lateral fluctuations of the wind would give an adequate measure of diffusive power, the output of the sensitive wind direction vane could be recorded for later analysis, or a parameter computed from it and recorded graphically or digitally. It is considered that this approach would be inadequate in this application and costs are not being presented. The next degree is to use a tri-axis anemometer as a sensor and to process its signals into pseudo-parameters for graphic or digital recording. In this approach the major consideration is the cost of "on-line" processing of each of the three signals. It would be economical to calculate only a single approximate function for each signal. For example, short-period maximum-deviation-from-the-mean costs about $300 per signal to calculate, a true "sigma" for fixed periods costs in the region of $3000 per signal channel. The calculated function can be recorded graphically at a cost of $600 per signal or recorded in an existing digital system at very little increment in cost. The third degree is to commit the signals from tri-axis anemometers into magnetic-tape storage and to rely for all parameters on an analysis of these records in storage. Only magnetic tape, electron oscilloscope, or light-beam galvanometer systems are known to record analogue signals with sufficient fidelity for subsequent spectral analysis. Suitable magnetic tape recorders cost about $9000 for seven signal channels, $14,000 for fourteen signal channels. A major cost is in the subsequent conversion and analysis of these recorded signals. While it is difficult to estimate costs of conversion and analysis because of the many factors involved, experience to date suggests costs in the vicinity of $30,000.

Tri-axis anemometers can be of several basic types, including sonic and three-component propeller-wheel, but the commercial units currently available are the bi-vanes with attached propeller wheels for windspeed. Three such anemometers are the Gill Anemometer Bivane, cat. 21001, Climet Axiometer, model CI-12 and the MRI Vectorvane, model 1053. Prices for these systems, without recorders, range from $1100 to $1400. The Gill vane has a D.C. generator tachometer for a windspeed transducer while the other two use a chopped light-beam system. The MRI Vectorvane system can record "sigma" of the two vane channels, and this is done on a two channel E-A graphic recorder at an additional cost of $1850. The Climet Model CI-12 also has an optional "sigma" output. If tri-axis anemometer outputs are to be stored for subsequent parameter analysis, the signals must be recorded on a low-hysteresis system such as f.m. magnetic tape. Records with pen and paper charts suffer from hysteresis distortion, resulting in intolerable spectrum distortions. Light-beam recorders do not suffer from this type of distortion, but such records present formidable data-extraction task. An example of f.m. magnetic tape recorders is the Geotechnical Corporation 7-channel recorder produced specifically for slow-speed geophysical and meteorological applications. Its cost is $8750. Standard I.R.I.G. 14-channel recorders with adequate signal monitoring cost about $14,000 each and may be purchased from any of several companies.

In viewing the tower instrumentation as a whole, it may appear that redundancy in wind sensors exist, and this is so if a tri-axis anemometer can also perform continuously the functions of a wind-speed and -direction instrument. This is not necessarily the case, and potential savings of up to $1600 per level may be illusory. The possibility should, however, be followed up and made a factor in assessment of tri-axis anemometers.

The cost of a 300-foot tower depends upon the cross-section of the tower. A 36-inch section tower with inside ladder and working level platforms, lights, paint, costs very close to $10,000 installed. A bare 20-inch section tower with lights and paint costs $5,000 installed. A 20-inch section would need a ladder and safety rail if it were to be climbed by instrument technicians. Alternatively, it is thought possible to have an instrument elevator on a 20-inch tower to ease instrument maintenance problems. Costs will be based on the 36-inch section tower as these should be adequate to cover other satisfactory patterns. Costs for removal of tower and restoration of site have not been included in costs of a 300-ft tower installation, nor have easement costs been included as it is assumed that installations of towers will be made on the Marshall reservation and that the towers would be retained for continuing meteorological measurements.

2.4.8 Measurements of Wind and Temperature Above 300-ft Height

The facilities of MSFC for rawin ascents using the GMD-2 rawin with Q9 sonde and the integrated A. D. P. system should give the type of information required. The experimental balloon ("Jimsphere") is likely to be needed to avoid the introduction of spurious oscillations into the data used to determine diffusion parameters. A number of ascents, closely spaced in time, would be specified. This may require some technical modification to the sonde to prevent interference between successive ascents.

Two double-theodolite pibal stations, one placed in the plain towards the east and another in Huntsville would reveal any areal variations in wind flow. These ascents should not be necessary above 5000 feet and termination height would be weather-dependent in any case.

2.4.9 Physical Facilities

The material resources required to undertake this experimental program are discussed briefly in this section. There are certain of these resources which must be furnished by the government (GFE) if an effective experiment is to be conducted. Such resources are indicated herein and are not included in the cost estimates. Other resources which could well be provided by the government are indicated as GFE optional but are included in the cost estimates. For convenience, a summary of the resources in each of these two categories is included at the end of this section.

A reasonably centralized location is required for a field operations center consisting of a building of approximately 3000 sq ft and ample parking space immediately adjoining for a minimum of ten vehicles.* Adequate space should be available within the building for an office consisting of about 400 sq ft and an instrument work shop of 300 sq ft. Standard plumbing and electrical facilities will be required. The space will be used for equipment layout and storage, personnel training, assembly, and management and administration of the operation. In addition, 150 sq ft of remotely located dry storage space will be required to store the tracer material and dispensing equipment. This material cannot be stored at the field operations center since it would contaminate the sensing instruments. The Operations Center is considered GFE optional; the dispenser and aerosol storage is required GFE.

Of the 262 sampling sites proposed in Plan C, 123 are believed to be on U.S. Government Property. The remaining sites are either on private property or municipal property. It is, of course, essential that the government

*These figures are for plan C. Plan A requires much less space.

authorize access to suitable sampling sites on government property. In most cases, a sampling site consists of a suitably open space where a metal fence post can be placed to hold the sensor during an experiment. In many cases it is anticipated that agreement can be reached with the local utility company to permit brief use of existing telephone poles. In some cases, however, individual agreements will be required with private property owners. In previous programs there has been little difficulty in obtaining public support for scientific experiments. The sequentializer samplers will in most cases be placed in the same locations as the rotobar sensors.

Of the twenty 70 ft tower sites selected in Plan C, eight are believed to be on government property. Authorization for use of the sites and construction of the towers would be required. The additional twelve sites are on municipal or private property and leases would be required. These towers will require installation of 110 V single phase power outlets for instrumentation. It is assumed the power would be provided GFE for the sites on government property.

Both sites for locating the 300 ft meteorological sensing towers are on government property. Authorization for use and construction of the towers, and for power installation is assumed to be government furnished.

Suitable storage in a hangar or warehouse for the four balloons will be required for Plan C. Four bays 40 ft long, 14 ft wide, and 20 ft high (total area 2240 sq ft) will be required with suitable doors to permit passage of the balloon wagons. One or two 12,000 cu ft helium tanks will also be stored in this area. If at all possible, the area should be secure and thereby prevent tampering with the somewhat fragile balloons. It is considered essential that this be GFE since it is necessary that the storage be as close as possible to the 3 km sensing arc.

Some fifteen balloon operating sites will be required. Ideally, an area 200 ft square free of neighboring obstruction is desirable. Each site would be equipped with two ground anchors and associated surface cable. It is essential that adequate space be made available by the government at or near the 3 km arc for these sites.

The following quantities of helium will be required for operation of balloons:

Initial inflations	20,000 cu ft
Topping-off	6,000 cu ft/month (eight months)
Pibal runs	2,000 cu ft/month (small tanks, 9 months)

The provision of helium is GFE optional.

Standard office furniture consisting of desks (4), tables (5), and chairs (4 desk and 15 folding) will be required in addition to customary office supplies. These items are considered GFE optional.

The following communications will be required:

a. Telephones—required at the Field Operations Center, source site, and balloon hangar. It is believed essential that telephone service be provided GFE for any of these sites which are on government property. If the operation center is GFE, it would also be desirable to authorize contractor use of government tie-lines or WATS service.

b. Radio Communications—Two-way radio communications (range of 9 miles) are required between all field assigned vehicles to permit coordination of the various operations. This is GFE optional but should, perhaps, be consistent with provision of the vehicles.

c. Facsimile—a facsimile line and receiver will be required for receipt of the standard weather charts for planning and scheduling experiments. This is GFE optional.

d. Walkie-talkies—up to eight walkie-talkie units (2 mile range) will be required for balloon system and tower maintenance purposes. This is GFE optional.

For routine field use, one station-wagon and one 1/4 ton pickup truck will be required full time. When experiments are scheduled, additional vehicles will be required depending on the plan adopted. The station wagons are required for transporting the sensitive instrumentation and the trucks for aerosol samplers in quantity. These are considered GFE optional. If they are to be GFE, it is recommended an adequate priority be assigned to assure availability, particularly during experiments.

<u>Summary of GFE Resource Items</u>

Required GFE:

a. Aerosol Sampling Sites.

b. Meteorological Surface Station Sites (8) with power.

c. Tower Sites (2) with power.

d. Balloon Storage.

e. Balloon Operating Sites (15).

f. Rawinsonde Observations—equipment and operation.

g. Source Sites.

h. Dispenser and Aerosol Storage.

i. Telephone for principal on-base sites.

j. Two L-19 class aircraft and one pilot.

Optional GFE:

a. Field Operations Center.

b. Office Supplies and furniture.

c. Helium.

d. Vehicles with two-way radios.

e. Facsimile Circuit and Receiver.

f. Walkie-talkies.

No attempt has been made to determine what, if any, instrumentation or operating personnel could be provided by NASA. Discussion in this regard is suggested.

2.5 Recommended Phasing, Operation and Manpower

The following section describes the phasing schedule for the field programs, operational procedures, manpower required for field operations and management functions.

2.5.1 Phasing

To accomplish a program of the magnitude and scope required to fulfill the technical objectives, a five phased program is recommended. During the first phase, Program Activation, the detailed analyses will be undertaken to determine the specific instruments to be employed in the program, considering the various trade-off factors of effectiveness, reliability, maintainability, cost, etc. The selected instruments will be processed, delivered to Huntsville, installed and checked-out. Concurrently the detailed logistical problems will be analyzed and solved following an initial site survey to be conducted as a first order of business. A minimum of three to six months is required to accomplish the program activation phase depending on the plan adopted. During the first four months of the activation phase for Plan C, the planning, procurement, etc., would be undertaken from the contractor 's home office. The Huntsville field operation would be activated during the fourth month to allow two months for installation, check-out, training and tests. Upon completion of the phase, all resources are in a state of readiness.

The second phase is the first of two four-month operational periods and should be conducted during the months of October through January to acquire seasonal data for the fall and winter periods. Test experiments would be conducted whenever operationally feasible.

The third phase, during February and March, is essentially a stand-by phase to await seasonal changes. However, during this phase all required instrument maintenance will be performed to assure high reliability during the ensuing operational period.

A second operational period constitutes the fourth phase and is identical with phase two except that it is conducted during April through July to acquire data during the spring and summer seasons.

The final or deactivation phase will require three weeks and involves the removal, packing and shipping of all instrumentation and equipment.

2.5.2 Operations—Spill Experiments

Twelve to twenty tests are proposed for each operating period to be conducted under various environmental conditions. The meteorological conditions desired are:

a. West through south-southwest winds to 500 ft with various speeds up to 25 mph.

b. Various stability conditions with one-third being inversions.

c. No precipitation or thunderstorms.

d. Base of clouds 1500 ft or higher (for balloon operations only, Plan C).

e. Visibility 3 miles or more (for balloon operations only, Plan C).

For experimental purposes, fluorescent particles will be dispersed into the atmosphere from the surface for periods up to 30 minutes per experiment at rates up to 10 gram/sec. To assist in defining the specific air trajectories for selecting balloon sites in Plan C, smoke releases will be made two hours before release time and occasionally again one hour before release.

Surface tracer sampling and meteorological measurements have been discussed previously. Details of sampling above the surface for Plan C are outlined below.

Four tethered balloon systems will be located at pre-selected sites, varying with the wind trajectory, along the 3 km arc. They will be placed 1000 ft apart and hence will cover a 3000 ft segment of the arc. Six airborne-type rotobars plus three combination sensor and light units will be carried on each system with vertical sensor spacing of 50 ft. A total of 36 samplers and 12 light units are required.

If aircraft sampling is performed, two light planes of the L-19 class will be equipped to measure and record aerosol concentrations continuously for total dosage and/or in short time increments to permit space and time resolution of the cloud material. The aircraft will fly concurrent lateral traverses through the cloud at assigned altitudes (this depends on the expected rate of vertical diffusion) south of the Madison County Airport and over Huntsville. At least three traverses will be made at each of the assigned altitudes and locations.

2.5.3 Static Firing Experiments

The number of tests required are considered to be five each operating period, ten total, to be conducted in conjunction with NASA scheduled tests, usually in the late morning or afternoon.

Meteorological conditions desired are:

a. West through south-southwest winds to 300 ft with various speeds up to 25 mph.

b. Various stability conditions.

c. No precipitation or thunderstorms.

d. Ceilings greater than 5000 ft and visibility greater than three miles for aircraft operations in Plan C.

As discussed in the tracer section, further analysis is required prior to final selection of the tracer for this experiment. However, it appears that a rare earth material is feasible for injection into the exhaust plumes, and it is assumed that the same aerosol sensors used in the spill experiments will be effective. The tracer will be disseminated for the full period of the static firing at a rate commensurate with sampling sensitivity, but the total amount required will be on the order of 10 lbs.

Ground sampling will be conducted with rotorods as outlined in the spill experiment but with a reduction in density to that outlined in Appendix A for all plans, and sequentializers in the same manner as described for the spill experiments. Vertical sampling will be conducted in the same manner as the spill case with an additional traverse near the source and altitudes appropriate to the source height.

2.5.4 Manpower and Management

Personnel requirements and costs are based on experience that the Travelers Research Center, Inc. has accumulated in conducting field programs of this type. Personnel costs listed in Section 2.7 are based on TRC cost schedules. The manpower and training requirements will be discussed for each of the prime functions involved in the operation during phases 2 and 4. In some cases the same individuals can perform dual functions with proper scheduling.

A field director and assistant will be provided by the contractor.

Two to four teams of two men each will be required for laying out and collecting the ground samplers. These people can be hired and trained locally. A contractor-provided supervisor will train and oversee the operations. Table 2.2 below lists positions and manpower requirements by Design Plan.

Instrument technicians will be required to install, operate and maintain all meteorological instrumentation. One technician should be from the contractor's permanent staff.

Two observers and one recorder will be required for each double theodolite observation site. Every attempt will be made to hire and train local personnel.

One locally hired person of suitable talents will be trained to operate the aerosol dispenser apparatus.

For balloon operations, a three man team is required to fly each balloon with the assistance of a roving two-man launch team. As a minimum, a balloon system supervisor will be provided by the contractor; it may also be necessary for the contractor to provide some site leaders, but attempts should be made to hire and train suitable personnel locally. Table 2.2 summarizes the manpower requirements for the field programs described.

TABLE 2-2
MANPOWER SUMMARY

Position	Plan A Number	Plan A Source	Plan B Number	Plan B Source	Plan C Number	Plan C Source
Field Director	1	TRC	1	TRC	1	TRC
Ass't Field Director	1	TRC	1	TRC	1	TRC
Secretary (part-time)	1	local	1	local	1	local
Instrument Technician	1/4	TRC	1	TRC	2	1-TRC
Aerosol Sampling Supervisor					1	
Sampling and Balloon Assistants	4	local	6	local	8	local
Pibal Observers	0		0		6	local
Dispenser Operator	1	local	1	local	1	local
Balloon System Supervisor	0		0		1	TRC
Balloon Site Chiefs	0		0		4	2-TRC
Balloon Launch Team	0		0		2	
Totals	8-1/4		11		28	
TRC	2-1/4		3		7	
Local	6		8		21	

Management of the field program will be accomplished by the contractor. The Travelers Research Center, Inc. would establish an operating location in the Huntsville area for the purpose of undertaking the proposed field experimental program. An experienced senior individual would be assigned as field director to be responsible for the conduct of the program. Administrative support will be provided from TRC, Hartford, to the maximum extent possible. All key positions will be filled by experienced TRC personnel. Additional TRC personnel would be used as required; however, every attempt will be made to hire and train suitable personnel locally as a means of reducing costs.

2.6 Data Analysis and Processing

Collection of tracer and meteorological information must be followed by assay, analysis and synthesis into final diffusion models that describe the processes that took place during the experimental program and the extension of these results into a prediction system that can be used routinely in the user's operations. Alternate assay techniques are discussed where alternative tracers are presented and alternate data reduction systems for meteorological information are considered based on the type of sensor output assumed. Costs of the alternatives are considered in Section 2.7.

2.6.1 Tracer Assay

Assay techniques for fluorescent pigments are comparatively inexpensive and reliable. The basic technique is to count the number of particles on a rotorod or filter with bright field microscopic techniques when the sample is illuminated with ultra-violet light at about 3600 Angstrom wave length. The fluorescent tracer particles are easily identified by their fluorescent color, and the number of particles on a rotorod are counted by traversing the rod through the field of view. Filter media are counted in much the same manner with a gridded eyepiece. Time required to count each sample varies with experience and amount of material collected. An informal quotation from one organization that does assay work was $2.00 per sample for rotorods exposed on one side in the quantities discussed here. Filters were quoted at $4 to $5 each. An investment of about $2000 will provide the necessary equipment to set up two counting stations (microscope with appropriate light sources for each), and the counting can be done by field personnel on a spare time basis between tests as an alternative to outside assay work. Investigation of other organizations which perform assays should be pursued, but the quotation received is considered here for cost estimates.

Aircraft sampling requires different procedures and collection devices because time resolutions of a higher degree than can be obtained with conventional filter media are required. For the past two years, Hanford Laboratories in Richland, Washington have been developing a device for automatically measuring and recording phosphorescence passing through the field of view. The device has the advantage of providing real time information to the observer in the aircraft, and he can actually search for a cloud of material. Positive collection is made and results can be checked at a later time so that calibration for each run is required. One area of concern is that nothing is known of the possible effect the exhaust material of the static test might have on the fluorescence of the tracer or possible contribution to fluorescence from the gases. Cost of the instrument with recorder is estimated at $5000.

Rare earth tracer assay requires elaborate analysis techniques, and the cost is high compared to fluorescent pigment. Present rates are quoted as $15.00 per sample, but previous processing has been done in limited quantities. Assays are performed by neutron activation and electronic counting methods rather than visual methods. One further disadvantage, aside from the cost of the tracer and assay, is the inability to make spot checks in the field to determine probable success of each experiment.

2.6.2 Meteorological Data Reduction

Referring to Section 2.4 for the surface wind and temperature system, two basic types of recording are described. One provides digital readout, and the only off-the-shelf model does not provide computer compatible tape; the second method is graphic analog recording of each sensing element. In this section, costs to prepare the information for entry into a computer for subsequent analysis are considered. Surface systems are designed to measure flow and not turbulence, therefore observations may be less frequent in time. The Climet CI-9 system is only capable of readout at two-minute intervals so graphical methods are assumed at the same rate for comparative purposes.

Assuming 10 hours of data per test at 20 stations with a total of 40 tests (all estimates are liberal to allow for aborts, delays, etc.), there will be 240.000 observations of wind direction and speed and with these temperature stations in the system, 36,000 observations of temperature. Thus there are a total of 516.000 observations assumed for all tests. Conversion of the Fisher-Porter tape to IBM punched cards costs \$2.00 per 1000 observations plus a fee of \$1.00 per tape. Therefore this cost from sensing to punched cards is \$1032, plus approximately \$300 for tape fee charges yielding a total of \$1332 for surface data reduction. Manual reduction of graphic records based on previous experience is estimated for 516,000 observations at \$2554. This figure is based on 2.8 man-hours per 1000 observations to read, record and key-punch graphically presented information. Estimates are further based on costs of \$1.75/hr wages and 5¢ per 1000 observations for cards. Considering the cost of the original equipment, the digital readout and conversion are less expensive and require less time to go from observations to computer-ready data.

Analysis costs are the same no matter how the data were prepared for the computer. It is assumed that means, variances, differences between stations, and summaries are required for analysis. Computer costs for this portion should not exceed \$1000 for Plans B or C.

Reduction and analysis of tower turbulence data described in Section 2.4 is a problem of much greater magnitude. If the sensing and recording system provides a true "sigma" value, very little processing is entailed beyond the data acquisition and subsequent correlation with tracer measurements. Analysis is severely limited because the "sigma" value is for a fixed time and Pasquill* has shown that for best comparison, the computed wind standard

*Pasquill, F., 1961, The estimation of dispersion of windborne material, The Meteorological Manazine, Vol. 90, 1063, Feb., 1961, 33-49.

deviations should be a function of travel time. Costs of this system are comparable to that of recording and analyzing f.m. magnetic tape so it is not deemed feasible.

If f.m. magnetic tape is used as the recording medium, the data may be processed in two ways. The analyses can be performed on analog computers to yield means, variances and power spectra or the data can be converted to digital input for processing in digital computers. Costs in both cases are similar and previous experience indicates an estimate of about $30,000 for processing data in the quantities expected from this program for Plan C and $20,000 for Plan B.

If slightly reduced amounts of information are compatible with the overall objectives of the program, considerable reduction in the analysis cost can be made by computing only the spectral analyses. Total variance can be measured from the spectrum and contributions from various averaging times can be obtained. Mean values are missing, but they are of least importance in turbulence measurements. This method of analysis can be accomplished through use of a General Radio Spectrum Analyzer if the tape recorder has the capability of loop playback. Additional hardware costs are in the vicinity of $4000, and associated personnel costs to set up the equipment and perform the analyses are estimated at $7000. While the information available is less complete than with a full scale data reduction program, it has the advantage that investigation may be more carefully controlled by the scientist using the information in relating it to measured dispersion rather than one large scale effort where all the data are analyzed at one time. Total costs are estimated at $11,000 for Plan C and $9,000 for Plan B.

2.6.3 Synthesis of Tracer and Meteorological Data Analyses

The primary objective of the experimental program described above is provide information that will enable MSFC users to adequately describe diffusion processes either through the use of existing models with experimentally determined parameters or through the use of newly developed models based on this program.

Some of the results and questions to be answered by the experimental program are listed below. Of course some can only be answered by the more complex designs of Plan B and Plan C.

a. Comparison of cloud trajectory with anemometer and balloon measured wind trajectories.

b. Are there preferred trajectories due to topography under different stability conditions?

c. Is the assumed statistical diffusion model adequate to describe the diffusion processes taking place?

d. Measure parameters necessary for use of diffusion model.

e. What is the ratio of peak to average concentration?

f. What is the effect of buoyancy on surface concentrations for static firing cases?

g. How are turbulence measurements at the towers related to the diffusion of material?

h. What is the distribution of material along the axis of translation of the cloud?

i. What is the crosswind distribution of material?

j. What is the vertical distribution of material?

k. Are there areas of anomalous dosage due to topography?

The above items are a partial list of the problems to be considered in the analysis of field experimental data. From here the analyst will proceed to describe the diffusion processes in the MSFC area with appropriate mathematical models for the area. Once the model has been developed, it may be supplied to the user as a computer program or a series of nomograms or both. Any assumptions or deficiencies in the model will be discussed along with its strong points so the user will be able to assess, at least subjectively, the confidence level of predictions made during routine operations.

2.7 Cost Analysis

Costs are presented below for each of the three experimental plans presented in the preceding sections. Objectives are stated once more for reference and items considered to be government furnished are listed. Cost summary sheets contain systems or groups of items, therefore additional tables have been included at the end of the section to show how equipment and installation costs were prepared by individual item.

2.7.1 Cost Summary for Plan A

Objective of Plan A — To verify predictions of peak concentrations and total dosage made with the model in part 1 of this report.

The following equipment and facilities are considered government furnished for this plan:

a. Field operations center with separate tracer storage area.
b. Office furniture and local telephone.
c. Sampling and source locations on government controlled property.
d. Rawinsonde observations—equipment and operation.
e. Vehicles—one pickup truck full time and one for tests only.

It is assumed that a satisfactory method of introducing fluorescent particles into the rocket plume will be developed for the costs in this plan. If this is not possible, an additional $17,000 will be required for tracer purchase and assay.

Plan A

Cost Summary

Equipment

2 Wind systems and 70 ft towers	$7500		
12 Sequential samplers and power supplies	5040		
80 Rotorods and batteries	7200		
1 FP Dispenser	3200		
2 Stations of assay equipment	2000		
2 Battery Chargers	160		$24,500

Supplies

200 lbs. Prepared FP	2280		
Filter tapes (48 rolls)	100		
Hardware and site preparation	400		2,780

Field Services

Salaries—part-time help 30 man months	10,800		
Vehicle Rental	2,000		
TRC Personnel living expenses, 540 days @ $15.00	8,100		20,900

Direct Costs

Salaries—Sr. Research Sci.	3 man-mos.			
Res. Scientist	10			
Staff Associate	10			
Electronic Tech.	2			
Sr. Research Aide	3			
Clerk	1	26,800		
Employee Benefits @ 30%		8,040		
Travel		1,800		
Other Direct Charges		1,045	$37,685	
G & A @ 70% of TDC		26,380		
			64,065	64,065
				$112,245

2.7.2 Cost Summary for Plan B

Objective of Plan B — To verify predictions of peak concentrations and total dosage made with the model in part 1 and to verify the horizontal diffusion coefficients and infer the validity of the estimated vertical diffusion coefficients.

The following facilities and equipment are considered government furnished for the costs of this plan:

a. Meteorological surface station sites with power (5).

b. Tower site with power.

c. Sampling and source locations on government controlled property.

d. Rawinsonde observations—equipment and operation.

e. Tracer storage area.

The following cost summary lists equipment, supplies and services to be supplied by the contractor in performance of this program.

Plan B

Cost Summary

Equipment

10 Surface Wind Systems and 70 ft towers	$37,500	
3 Temperature Systems	4,400	
1 300-ft tower	10,200	
3 tri-axis anemometers	7,350	
1 IRIG f.m. Tape Recorder	13,000	
3 Tower Temperature System	3,570	
1 FP Dispenser	3,200	
19 Sequential Samplers and power supplies	7,980	
185 Rotorod samplers and batteries	16,600	
Site Preparation	1,000	
2 Sets, assay equipment	2,000	
2 Battery chargers	150	
Mobil radio net.	2,300	$109,250

Supplies

180 lbs. FP assayed	2,050	
Magnetic Tape	1,000	
Filter Tapes	125	
Local Hardware Purchases	600	3,775

Plan B (cont.)

Field Services			
Salaries for part-time (56 months)		$23,100	
Car and Truck rental		6,600	
Facsimile rental @ 106/mo.		1,378	
Facsimile supplies		1,122	
Land rental—instrument sites		300	
Office Rental		4,000	
Utilities		500	
Furniture Rental		400	
TRC Personnel living expenses		15,950	$53,350
Data Reduction and Computations			
f.m. Tape reduction		20,000	
Surface station analysis		10,000	30,000
Rare Earth Tracer		1,000	
Assay		22,000	23,000
			219,375
Direct Costs			
Salaries—Sr. Res. Scientist	4 man months		
Res. Scientist	18		
Staff Associate	12		
Electronic Technician	10		
Sr. Research Aide	6		
Clerk	3	$47,073	
Employee Benefits @ 30%		14,122	
Total Labor		61,195	
Travel		4,900	
Other Direct Charges		1,530	
Total Direct Charges		67,625	
G & A @ 70% TDC		47,338	
Total		114,963	$334,338

2.7.3 Cost Summary for Plan C

Objective of Plan C — To verify predictions of peak concentrations and total dosage made with the model in part 1, verify horizontal and vertical diffusion coefficients, and develop comprehensive diffusion prediction techniques.

The following facilities and equipment are considered government furnished for the costs of this plan.

a. Meteorological surface station sites with power (8).

b. Tower sites with power (2).

c. Balloon storage.

d. Balloon operating sites.

e. Rawinsonde observations—equipment and operation.

f. Tracer storage area.

g. Sampling and source locations on government controlled property.

h. Telephone for principal on-base sites.

i. Two L-19 class aircraft and one pilot.

The following summary lists equipment, supplies and services to be supplied by the contractor in performance of this program.

Plan C

Cost Summary

Equipment

20	Surface Wind Systems and 70 ft towers	$80,000
3	Temperature Systems	4,395
2	300-ft towers	20,400
6	Tri-axis anemometers	14,700
6	Level of Temp.	7,140
6	Wind speed and Direction units	21,100
2	f.m. Tape recorders	26,000
2	Pibal stations and associated equipment	8,560
1	FP dispenser	3,200
24	Sequential Samplers	10,080
275	Rotorod samplers and batteries	24,500

Plan C (cont.)

Site preparation	$1,400	
2 Sets assay equipment	2,000	
3 Battery Chargers	225	
Aircraft sampling instrumentation	6,000	
Maintenance Facilities, parts and equipment	3,210	
4 Balloon systems	35,976	
Auxiliary balloon equipment and spares	4,940	
1 Mobil radio net.	3,100	$276,931
Supplies		
Balloon supplies	$7,768	
Tracer FP	1,710	
Rare earth (if required)	2,100	
Magnetic tapes	2,000	
Filter tapes	200	
Local hardware supplies	1,200	14,978
Data Reduction and Computations		
f.m. Tape reduction	30,000	
Surface station and model preparation	15,000	45,000
Rare Earth Assay	31,000	31,000
		$367,909
Field Services		
Salaries—part-time	58,114	
Car and truck rental	22,985	
Facsimile rental @ $106/mo.	1,378	
Office rental @ $300/mo.	4,550	
Utilities @ $40/mo.	520	
Facsimile supplies	1,122	
Land rental—instrument sites	600	
Furniture rental	500	
TRC personnel living expenses	42,600	
Consultants (airborne samplings, etc.)	1,800	$134,169

Direct Costs

Sr. Res. Scientist	8 man months
Research Scientist	27
Associate Scientist	40
Electronic Technician	20

Plan C (cont.)

Staff Scientist	17 man months		
Senior Research Aide	21		
Clerk	5	$119,186	
Employee benefits @ 30%		35,756	
Total Labor		155,942	
Travel		8,931	
Other Direct Costs (3.5% %L)		3,874	
Total Direct Costs		167,747	
G & A @ 70% of TDC		117,423	
Total Direct Costs		285,170	$285,170
			$787,248

TABLE OF COSTS FOR A SURFACE WIND AND TEMPERATURE MEASUREMENT STATION

—detailed for graphic recording of signals
—includes maintenance costs for one year

70-ft tower			
Tower, installation, removal, restoration	$550		
Easement for installation	100		
Power—fittings, connection	50		$700
Wind-speed and direction instrumentation			
Sensors and electronics	1600		
Graphic Recorders	1200		
Cabling	150		
Recording Shelters	100	$3050	
Maintenance 0.05 man @ 250/yr		250	3300
*Air temperature instrumentation			
Sensor	100		
Aspirator	340		
Recorder	850		
Cabling	25		
Shelter (part of w/s system)		$1315	
Maintenance 0.02 man @ 150/yr		150	1465

*At stations selected for measuring surface temperature.

TABLE OF COSTS FOR AN ELEVATED WIND
AND TEMPERATURE MEASUREMENT STATION

—detailed for graphic recording of signals
—includes maintenance costs for one year

<u>300-ft tower</u>				
Tower, installation, paint, lighting		$10,000		
Power, fittings, connection		200	$10,200	
<u>Wind-speed and direction instrumentation</u>				
As for surface station, 3 @ 3050		9,150		
Installation and removal assistance		400		
Maintenance—0.1 man @ $1000/yr		1,000	$10,550	
<u>Air Temperature Instrumentation</u>				
Sensor	100			
Aspirator	340			
Cabling	150 —3 @590	1,770		
Multichannel potentiometric recorder		1,500	3,270	
Maintenance 0.04 man plus $300/yr			300	$3,570
<u>Air Turbulence Instrumentation</u>				
Sensors and electronics	1400			
Cabling (average)	250 —3 @ 1650	4,950		
Installation and removal assistance		400	5,350	
Maintenance 0.2 man @ $2000/yr			2,000	$7,350
<u>Recorder for air turbulence signals</u>				
IRIG Magnetic tape recorder, 10 ch. record., with monitor		13,000		
Magnetic tape, estimate		1,000	14,000	
Maintenance 0.04 man @ $200/yr			200	14,200

TABLE OF COSTS AND REQUIREMENTS FOR AEROLOGICAL SOUNDINGS

Rawinsonde to 10,000 feet

System: MSFC's GMD-2, ADP
Definition: 50 meters
Frequency: 15 minute intervals
Number: 6 to 12 per experiment
Responsibility: MSFC

Double Theodolite Ascents to 5000 feet (two stations)

Warren-Knight theodolite (4)			$4000		
Pibal timers (2)			180		
Communication headsets (6)			250		
Power arrangements			50		
Communications cable (or commercial line rental)			300	$4780	
Supplies per experiment:	Balloons	$10			
	Helium	25			
	Lighting Units	10	45		
Training flights and aborts:			45		
One Year: 42 @			90	3780	$8560

AEROSOL GENERATION AND SAMPLING FOR SURFACE SOURCE

<u>Generation</u>			
Fluorescent Particle Dispenser		$3200	
Fluorescent Pigment—assayed, 150 lb.		1710	$4910
<u>Surface Sampling</u>			
Rotorod samplers—purchase and modification 275 @ $80		$22,000	
Location costs—280 @ $5		1,400	
Batteries for 40 exp.—1250 @ $2.00		2,500	$25,900
<u>Sequential Sampling at Surface</u>			
Incremental Sampler	345		
Power Inverter	50		
Battery	25		
24 @	420		10,080
Portable tower for source sampling			300
Sampling on fixed 300 ft tower - fittings			100
Analysis equipment for rotorod samplers (single station) —Ultraviolet lamps, traveling stage microscope			1,000
			42,290

BALLOON SYSTEM COSTS

I. Equipment

1. Balloon Equipment

a.	Balloon System Design: \$3,000; 750/system	\$750.00
b.	Balloon—Aerodynamic, 2,000 cu ft (in quantities of 4) 45# to 450 ft.	4,500.00
c.	Lights—tetherline and balloon, 4 @ \$100	400.00
d.	Rotorod Samplers: 6 airborne units, 1 spare @ \$100; 6 auxiliary units for lights, 1 spare, \$25	800.00
e.	Tether—2 600 ft lines, 2000# @ \$.08/ft	96.00
f.	Winch or Capstan—gasoline, 2000# capacity	520.00
g.	Power Cable—600 ft @ \$.03/ft	18.00
h.	Ground Power—switching	50.00
i.	Balloon Wagon—special design	1750.00
j.	Balloon Tool Kit and Miscellaneous Hardware	85.00
k.	Pulleys	25.00
	Cost per balloon system	\$8994.00
	Four balloon systems	35,976.00

2. Auxiliary Equipment

a.	Tether Point Ground Anchors, 30 @ \$8.00	240.00
b.	Walkie-talkies, 6	200.00
c.	Spare Balloon	4,500.00
		4,940.00
	Total Equipment	\$40,916.00

II. Supplies

a.	Ground Power Source—batteries, \$20/trial x 18	\$360.00
b.	Rotorod batteries—\$54/exp. x 15	810.00
c.	Helium	

(1) Inflations 2000 cu ft x 10 = 20,000 ft^3
x .09¢/cu ft; 1,800.00

(2) Topping-off: 50 ft^3/day/balloon, 6000 ft^3/mo., 12,000 cu ft tank, 2 mos., \$1080; Tank rental 100; Two mos., \$1180			
\$1180 x 4 mos., \$4,720.00	—	Helium	\$6,520.00
d. Nylon line, 2000 lb. test; 500 ft x \$.06			30.00
e. Fence Posts—24 @ \$2.00			48.00
		Total Supplies	\$7,768.00

COST DATA — TRACER STUDIES

Neutron Activation

Analysis — by General Atomic Division of General Dynamics Corporation; Approximately $15.00/sample for 2000 samples.

Tracer Materials —

Source (99.0% Pure)	Tracer (Oxides of metals shown)			
	Dy	Eu	Ir	In
Michigan Chemical Corp.	$50/lb.	$1000/lb.	—	—
A. D. MacKay, Inc.	105	700	2,240	99
Lindsay Chemical Div., American Potash & Chemical Corp.	105	635	—	—
Vitro Chemical Co.	60-70	—	—	—
Engelhard Industries, Inc.	—	—	1,364	—
Davison Chemical Company	272	1,245	—	—

Actual quantities required cannot be determined until sensitivity tests have been run with rotorod samplers. Preliminary estimates indicate 22 lbs. of tracer would be adequate for 10 static firings of 2 min. each. Dysprosium will be used if possible.

Fluorescent Pigment

Analysis—Utah State University — Not determined
MRI; $2.00/rotorod in lots of 100
(2 arms — 1 side each)
Metronics; $3.25/rotorod

Source of Zinc Cadmium Sulphide		Cost
U.S. Radium	1-4 lbs.	$6.90/lb
	100-500 lbs.	4.75
	Pigment count and spectrum would have to be determined.	
Metronics	Fluidized and packaged	$7.90/lb.
	Completely fluidized, assayed, packaged in 1500 gram "squeeze bottle"	$11.40/lb.

Approximately 145 lbs of pigment will be required for 24 thirty-minute releases.

2.8 Summary

An experimental program has been presented for MSFC with three alternatives of complexity and cost which lead to different solutions for the problem of atmospheric diffusion in the Huntsville area. The basic experimental design is the same for all programs, i.e., use of an aerosol tracer to measure diffusion of material and resultant surface concentrations. As the complexity and costs increase so does the understanding of the diffusion processes.

Site visitation, perusal of topographic maps of the area, and an appeal to some of the available climatological data have led to a design that anticipates a curvature in the trajectory of material released from the static test area in a wind flow that would result in material reaching Huntsville. Outer sampling arcs have been adjusted to account for this assumed trajectory. Several anemometer locations were suggested to measure the local wind direction and speed during tracer trials and to provide a climatology of flow by continuous recording during the experimental period.

A thorough mathematical analysis of the statistical diffusion model was prepared to ensure the sampling density would be satisfactory but not excessive. Most tracer programs designed to evaluate dispersion processes in the atmosphere provide measurements of integrated concentration (or total dosage) and the variance of the concentration. A third important measurement is that of peak concentration, therefore provisions were made for determining this quantity. Peak concentration is the most variable of the three parameters; therefore the degree of accuracy required for that variable was the basis for the density of the sampling network. The design provides for estimates correct within a factor of 2 at 90 percent confidence for moderately stable atmospheric conditions. The accuracy improves until stability decreases to conditions of superadiabatic lapse rate where looping occurs and material could be lofted over a sampling arc, but in this case the statistical diffusion model rapidly loses validity for short term concentrations.

Plan A was designed for minimum cost to provide tracer results that would confirm or deny that modeling studies, presented in part 1 as well as actual measurements of dosage in the MSFC—Huntsville complex.

Plan B was designed as a practical program to go beyond the minimum results available from Plan A and provide estimates of the rate of horizontal dispersion applicable to the Huntsville area for use in prediction programs.

Plan C was designed as a comprehensive, but not inflated, program to provide results like Plan A and B with additional information on vertical diffusion rates and more detailed meteorological measurements for preparation of prediction programs that would result in minimum lost time with meteorological control of operations.

APPENDIX A

by

Joseph G. Bryan

APPENDIX A. TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

APPENDIX A. STATISTICAL DESIGN OF AN OBSERVATIONAL NET FOR THE MEASUREMENT OF DIFFUSION IN THE LOWER ATMOSPHERE

1. Introduction

This analysis concerns the requisite spacing of observations in space and time for the attainment of a given level of accuracy in the definition of the field of concentration of an atmospheric pollutant. The analysis in space is based on the hypothesis that the expected or population distribution of concentration normal to the direction of travel is Gaussian. Field measurements from continuous point source tracer releases of 30 minutes duration are used to establish the variability characteristics within the population. For lack of suitable sequences of instantaneous concentration measurements the analysis in time is applied to the same data under the assumption that the localized distributions in the direction of the wind are the same as those normal to the wind and that the cloud moves uniformly with the speed of the wind. Although the method of analysis is quite general, the numerical results derived from it depend on the variability properties of these data. For this reason the results should not be extrapolated to design problems involving appreciably different sampling times or distances without due regard to the expected concentration variabilities.

For analysis purposes in the present problem the observational net over a horizontal cross section is assumed to be in the form of a polar array. By a polar array is meant a plane configuration described by concentric circular arcs, each of which is subdivided into a number of equal segments, although the proportionate subdivisions are not necessarily the same for different arcs. The equal central angles subtended by the equal segments of a given arc will be termed the angular separation along that arc. Given that observation posts for the measurement of atmospheric diffusion of contaminants are disposed in polar array over a horizontal plane, and assuming Gaussian distributions of concentration, except for random deviations, there are three design problems to which the present analysis is addressed:

(1) To derive approximate representations of the error distributions of sample estimates of concentration parameters, as a function of separation between observations.

(2) To determine the maximum angular spacing that will assure, with 90% confidence, that the ratio of an actual to estimated concentration parameter shall not exceed a stated upper tolerance limit.

(3) To determine the greatest time interval between measurements that will assure, with 90% confidence, that the ratio of actual instantaneous peak concentration to estimated instantaneous peak concentration shall not exceed a stated upper tolerance limit.

2. Summary of Principal Results

Attention was centered on statistics related to three parameters:

(1) Integrated Concentration: Ratio of Estimated Integral to Actual Integral—Symbol I_0

(2) Variance of Concentration: Ratio of Estimated Variance to Actual Variance—Symbol s^2 (Also $s = \sqrt{s^2}$)

(3) Peak Concentration: Ratio of Actual Peak Concentration to Estimated Peak Concentration—Symbol M ($M = r_0 s/I_0$) (Also $m = \log M$) (Notice that in the first two, the estimated value is in the numerator but in the third, the estimated value is in the denominator.) The sampling mean and variance were derived for the first two statistics, the square-root of the second, and the log of the third—also for certain other statistics. Approximate distributions were obtained by regarding I_0, s, and m (= log M) as normal variates. Evidence is presented in Section 7 to support the hypotheses of normality. The means and variances, recorded in Table 1, are expressed in terms of two basic parameters, Δ and σ_r^2, where

Δ = space between observations in units of the standard deviation of the distribution of concentration

σ_r^2 = variance of r where r is a random variable defined by

$$r = \frac{\text{Actual concentration}}{\text{Gaussian concentration}}$$

The spacing of observational posts is dictated by the sampling accuracy of the estimated peak concentration, for this has the greatest error variance. Graphs of the upper 90% confidence limit of M = antilog m = $r_0 s/I_0$ as a function of σ_r, for selected values of Δ, are shown in Fig. 1. Based on empirical evidence from Dry Gulch, [1] it is estimated that $\sigma_r = 0.25$. If an additional measurement error having a standard deviation of 15% is superimposed on the Dry Gulch estimate, the result will be $\sigma_r = 0.29$. Fig. 1 displays values of σ_r from 0.25 to 0.50 (corresponding to four times the variance indicated by Dry Gulch data). It is concluded from Fig. 1 that $\Delta = 2$ would be an acceptable spacing to assure $M \leq 2$ with 90% confidence.

Specifications for angular spacing and time spacing between observations at a given observation post have been determined so as to assure that $M \leq 2$ with 90% confidence. Angular spacing requirements were based on values of σ_y considered appropriate for stable conditions. Time spacing requirements were arrived at by assuming that the localized distribution of concentration in the x direction is the same as that in the y direction over relatively small distances (scale comparable to a small multiple of σ_y) and that the cloud moves uniformly with speed $\bar{u}$. The specifications listed in Table 2 are based on $\bar{u}$ = 3 meters/sec. and values of σ_y as indicated in the table.

TABLE 1
MEANS AND VARIANCES

Statistic	Symbol	Mean	Variance
Integrated Concentration: Estimated/Actual	I_0	1	$\frac{\sigma_r^2 \Delta}{2\sqrt{\pi}}$
Variance of Concentration: Estimated/Actual	s^2	1	$\frac{3\sigma_r^2 \Delta}{8\sqrt{\pi}}$
Standard Deviation of Concentration: Estimated/Actual	s	$1 - \frac{3\sigma_r^2 \Delta}{64\sqrt{\pi}}$	$\frac{3\sigma_r^2 \Delta}{32\sqrt{\pi}}$
Peak Concentration: log (Actual/Estimated)	$m = \log M$ $= \log(r_0 s/I_0)$	$\left(\frac{5\Delta}{32\sqrt{\pi}} - 1/2\right)\sigma_r^2$	$\left(1 + \frac{27\Delta}{32\sqrt{\pi}}\right)\sigma_r^2$

TABLE 2
SPECIFICATIONS FOR ANGULAR SPACING AND TIME SPACING
TO ASSURE M $\leq$ 2 WITH 90% CONFIDENCE

($\bar{u}$ = 3 meters/sec.)

x (kilometers)	σ_y (meters)	Angle (degrees)	Time (minutes)
1	68	7.8	0.76
2	125	7.2	1.39
3	180	6.9	2.00
4	235	6.7	2.61
5	275	6.3	3.06
6	325	6.2	3.61
7	370	6.1	4.11
8	420	6.0	4.67
9	460	5.9	5.11
10	500	5.7	5.56
11	548	5.7	6.09
12	582	5.6	6.47
13	630	5.6	7.00
14	670	5.5	7.44
15	710	5.4	7.96

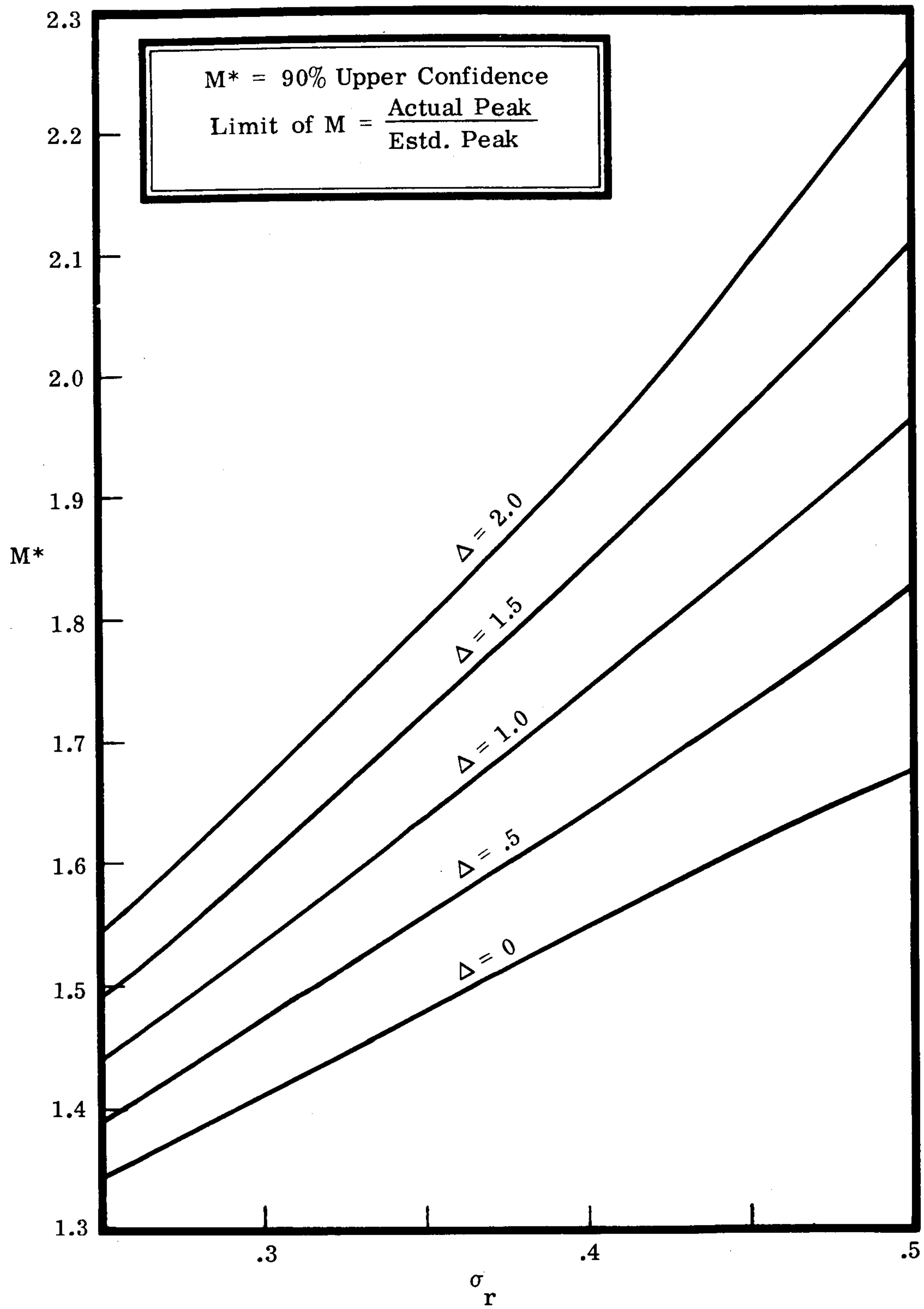

Fig. 1. Graphs of M* vs σ_r for selected values of Δ

3. Formulation of Statistical Model

It is assumed that the underlying distribution of concentration along an arc of the observational net is Gaussian, but that individual observations depart from the Gaussian values by independent random factors. Thus, if the Gaussian concentration at observation post i is denoted by f_i and the actual observation by a_i, the corresponding random factor r_i is defined so as to satisfy the equation,

$$a_i = r_i f_i \qquad (r_i \geq 0) \tag{1}$$

Let y_i denote the signed distance (coordinate measured along the arc) of observation post i from the axis of peak Gaussian concentration (at which location $y = 0$) and let Δ denote the uniform distance, along the arc, between observation posts. For convenience, both y_i and Δ are taken to be measured in units of the true standard deviation. In effect, then, this expedient sets $\sigma_y = 1$, and in ordinary usage Δ is to be interpreted as a multiple of the standard deviation, as measured in meters.

The statistics under consideration are of two kinds, direct and indirect. Regarded as direct statistics are the relative moments, designated as I_0, I_1, I_2. The indirect statistics, s^2 for example, are functions of the relative moments.

The relative moments are defined as follows.

$$I_0 = \sum_i a_i \Delta = \sum_i r_i f_i \Delta \tag{2}$$

$$I_1 = \sum_i y_i a_i \Delta = \sum_i y_i r_i f_i \Delta \tag{3}$$

$$I_2 = \sum_i y_i^2 a_i \Delta = \sum_i y_i^2 r_i f_i \Delta \tag{4}$$

The relative variance, s^2, is defined as a function of the relative moments by the equation,

$$s^2 = \frac{I_2}{I_0} - \left(\frac{I_1}{I_0}\right)^2 = \frac{I_0 I_2 - I_1^2}{I_0^2} \tag{5}$$

$$s = \sqrt{s^2}$$

The variate r_0, used to define M, has theoretical existence although it is not actually accessible to observation. It is defined in the following manner. Let a_0 denote the actual peak concentration (not necessarily located at $y = 0$, and not necessarily included in the observations) and let f_0 denote the peak Gaussian concentration (which does occur at $y = 0$); then the formal definition of r_0 is given by

$$a_0 = r_0 f_0 \tag{6}$$

a_0 = Actual peak

f_0 = Gaussian peak

The estimated Gaussian peak $\hat{f}_0$ has the formal definition,

$$\hat{f}_0 = \frac{I_0}{s} f_0 \tag{7}$$

and so the quotient M of actual peak and estimated peak is given by

$$M = \frac{a_0}{\hat{f}_0} = \frac{r_0 s}{I_0} \tag{8}$$

The statistical hypotheses are that the factors r_i are independently and identically distributed with unit mean and that I_0, s and $m = \log M$ are distributed normally. The immediate task is to derive the means and variances of I_0, s^2, s, and m. (Here s^2 is included for the sake of general interest, but it is s that is assumed to be normally distributed.) This will require also the determination of the means and variances of I_1 and I_2 as well as the three covariances between I_0, I_1, and I_2. Before undertaking this task, a numerical feature of the normal curve will be cited.

4. A Numerical Feature of the Normal Curve

The two parameters of the normal curve, considered as an exact mathematical function, can be determined precisely from two exact points, and the three parameters of a Gaussian distribution of concentration can be determined precisely from three exact points. However, in neither case would the method of moments be used. Nevertheless, the purpose of this section is to bring out the fact that the method of moments does yield good approximations, even with wide spacing and few points, if the function is truly normal. The practical importance of this fact is that it can be turned around to allow integrals to replace certain finite sums, involved in the means, variances, and covariances of I_0, I_1 and I_2.

Assuming an exact normal distribution, hence setting $r_i = 1$, the quantities I_0, I_1, I_2, s^2, s, and $a_0/\hat{f}_0$ (equations 2-5, 8) were evaluated for the unit normal curve under different values of Δ (Δ = 1.0, 1.5, 2.0) and with the "grid" system (observation points) displaced by various amounts ("shifts" of 0.00, 0.25, 0.50, 0.75) with reference to the true center of the curve. The main results of the calculations are shown in Table 3. Although the number of points used varied from 7 with Δ = 1 to 3 with Δ = 2, the numerical accuracy remained high. In the case of the estimated location of the center, given by I_1/I_0, a shift of the grid by a given amount in the opposite direction would yield an estimate of equal magnitude but opposite sign.

5. Means, Variances, and Covariances of the Relative Moments I_0, I_1, I_2

In general if $x_1, x_2, \ldots, x_n$ are independent variates having a common mean μ and a common variance σ^2 and if L_1 and L_2 are linear functions of these variates, such as

TABLE 3

ESTIMATION OF UNIT NORMAL PARAMETERS USING FINITE MOMENTS WITH DIFFERENT GRID SPACINGS AND DISPLACEMENTS

Shift	Statistic	7-ordinate scheme $\Delta = 1.0$	5-ordinate scheme $\Delta = 1.5$	3-ordinate scheme $\Delta = 2.0$
0	I_0	.9997	1.0000	1.0138
	I_1/I_0	0	0	0
	s	.9977	.9965	.9231
	$\frac{\text{Actual peak}}{\text{Estimated peak}}$	.9980	.9965	.9105
.25	I_0	.9995	1.0000	1.0094
	I_1/I_0	.0009	.0015	.0337
	s	.9970	.9978	.9426
	$\frac{\text{Actual peak}}{\text{Estimated peak}}$	.9975	.9978	.9338
.50	I_0	.9991	.9998	.9982
	I_1/I_0	.0032	.0021	.0513
	s	.9947	.9999	.9883
	$\frac{\text{Actual peak}}{\text{Estimated peak}}$	.9956	1.0001	.9901
.75	I_0	.9979	.9990	.9856
	I_1/I_0	.0071	.0022	.0459
	s	.9900	.9995	1.0297
	$\frac{\text{Actual peak}}{\text{Estimated peak}}$	.9921	1.0005	1.0447

$$L_1 = b_1x_1 + b_2x_2 + \dots + b_nx_n$$
$$L_2 = c_1x_1 + c_2x_2 + \dots + c_nx_n \tag{9}$$

then the means and variances and the covariance of the L's are given by the formulas

$$\text{Mean } (L_1) = \mu\,(b_1 + b_2 + \dots + b_n)$$
$$\text{Mean } (L_2) = \mu\,(c_1 + c_2 + \dots + c_n)$$
$$\text{Var } (L_1) = \sigma^2\,(b_1^2 + b_2^2 + \dots + b_n^2) \tag{10}$$
$$\text{Var } (L_2) = \sigma^2\,(c_1^2 + c_2^2 + \dots + c_n^2)$$
$$\text{Cov } (L_1, L_2) = \sigma^2\,(b_1c_1 + b_2c_2 + \dots + b_nc_n)$$

These formulas, applied to I_0, I_1, I_2 under the hypothesis that the r's are independent and that

$$\text{Mean } (r_i) = 1\,, \qquad \text{Var } (r_i) = \sigma_r^2 \quad \text{all } i \tag{11}$$

lead to the following equations:

$$\text{Mean } (I_0) = \sum_i f_i\Delta \tag{12a}$$
$$\text{Mean } (I_1) = \sum_i y_i f_i\Delta \tag{12b}$$
$$\text{Mean } (I_2) = \sum_i y_i^2 f_i\Delta \tag{12c}$$

$$\text{Var } (I_0) = (\sigma_r^2\Delta) \sum_i f_i^2\Delta \tag{13a}$$
$$\text{Var } (I_1) = (\sigma_r^2\Delta) \sum_i y_i^2 f_i^2\Delta \tag{13b}$$
$$\text{Var } (I_2) = (\sigma_r^2\Delta) \sum_i y_i^4 f_i^2\Delta \tag{13c}$$

$$\mathrm{Cov}\,(I_0, I_1) = (\sigma_r^2\Delta) \sum_i y_i f_i^2 \Delta \tag{14a}$$

$$\mathrm{Cov}\,(I_0, I_2) = (\sigma_r^2\Delta) \sum_i y_i^2 f_i^2 \Delta \tag{14b}$$

$$\mathrm{Cov}\,(I_1, I_2) = (\sigma_r^2\Delta) \sum_i y_i^3 f_i^2 \Delta \tag{14c}$$

Now replace all sums by corresponding integrals. To this end, remembering that the scale has been reduced to sigma units, write

$$\left.\begin{aligned} \sum_i y_i^n f_i \Delta &\approx \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} y^n e^{-y^2/2} dy \\ &= 0 \text{ if } n \text{ is odd} \\ &= 1 \text{ if } n = 0,\ 2 \\ &= 3 \text{ if } n = 4 \end{aligned}\right| \tag{15}$$

Further, for the terms involving f_i^2, first make the substitutions

$$\zeta = y\sqrt{2}, \quad h = \Delta\sqrt{2}, \quad d\zeta = (\sqrt{2})dy \tag{16}$$

and put

$$f_i^2\Delta = \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{\sqrt{2\pi}} e^{-y_i^2}\Delta = \frac{1}{2\sqrt{\pi}} \cdot \frac{1}{\sqrt{2\pi}} e^{-\zeta_i^2/2} h \tag{17}$$

whence

$$\left.\begin{aligned} \sum_i y_i^n f_i^2 \Delta &= \frac{1}{2\sqrt{\pi}} \cdot \frac{1}{(\sqrt{2})^n} \cdot \sum_i \frac{1}{\sqrt{2\pi}} \zeta_i^n e^{-\zeta_i^2/2} h \\ &\approx \frac{1}{2\sqrt{\pi}} \cdot \frac{1}{(\sqrt{2})^n} \cdot \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \zeta^n e^{-\zeta^2/2} d\zeta \\ &= 0 \quad \text{if } n \text{ is odd} \\ &= \frac{1}{2\sqrt{\pi}} \quad \text{if } n = 0 \\ &= \frac{1}{4\sqrt{\pi}} \quad \text{if } n = 2 \\ &= \frac{3}{8\sqrt{\pi}} \quad \text{if } n = 4 \end{aligned}\right| \tag{18}$$

When (15) and (18) are applied to (12), (13) and (14), the results are those exhibited in Table 4.

TABLE 4
MEANS, VARIANCES, AND COVARIANCES
OF I_0, I_1, I_2

Statistic	Mean	Variance	Pair	Covariance
I_0	1	$\sigma_r^2\Delta/2\sqrt{\pi}$	I_0, I_1	0
I_1	0	$\sigma_r^2\Delta/4\sqrt{\pi}$	I_0, I_2	$\sigma_r^2\Delta/4\sqrt{\pi}$
I_2	1	$3\sigma_r^2\Delta/8\sqrt{\pi}$	I_1, I_2	0

6. Means and Variances of the Derived Statistics s^2, s, m

The first step toward determining the means and variances of s^2, s, and m is to expand each in a Taylor series through terms of second degree. Define variables ϵ_0, ϵ_1, ϵ_2, ϵ_3 as deviations of I_0, I_1, I_2, r_0 from their respective means:

$$\left.\begin{aligned} I_0 &= 1 + \epsilon_0 \\ I_1 &= \epsilon_1 \\ I_2 &= 1 + \epsilon_2 \\ r_0 &= 1 + \epsilon_3 \end{aligned}\right| \qquad (19)$$

where ϵ_3 is assumed to be independent of ϵ_0, ϵ_1, and ϵ_2. Expected values (means) that will be needed shortly are stated here for future reference.

$$\left.\begin{aligned} &E(\epsilon_0) = E(\epsilon_1) = E(\epsilon_2) = E(\epsilon_3) = 0 \\ &E(\epsilon_0^2) = \frac{\sigma_r^2\Delta}{2\sqrt{\pi}}, \quad E(\epsilon_0\epsilon_1) = 0 \end{aligned}\right| \qquad (20)$$

$$\left.\begin{aligned}
E(\epsilon_0\epsilon_2) &= \frac{\sigma_r^2\Delta}{4\sqrt{\pi}}, & E(\epsilon_0\epsilon_3) &= 0 \\
E(\epsilon_1^2) &= \frac{\sigma_r^2\Delta}{4\sqrt{\pi}}, & E(\epsilon_1\epsilon_2) &= 0 \\
E(\epsilon_1\epsilon_3) &= 0, & E(\epsilon_2^2) &= \frac{3\sigma_r^2\Delta}{8\sqrt{\pi}} \\
E(\epsilon_2\epsilon_3) &= 0, & E(\epsilon_3^2) &= \sigma_r^2
\end{aligned}\right| \qquad (20)$$

The functions to be expanded are

$$s^2 = \frac{I_2}{I_0} - \frac{I_1^2}{I_0^2} = (1+\epsilon_2)(1+\epsilon_0)^{-1} - \epsilon_1^2(1+\epsilon_0)^{-2} \qquad (21)$$

$$s = \sqrt{s^2} = [(1+\epsilon_0)(1+\epsilon_2) - \epsilon_1^2]^{1/2}/(1+\epsilon_0) \qquad (22)$$

$$m = \log\left(\frac{r_0 s}{I_0}\right) = \frac{1}{2}\log[(1+\epsilon_0)(1+\epsilon_2) - \epsilon_1^2] - 2\log(1+\epsilon_0) + \log(1+\epsilon_3) \qquad (23)$$

When these are expanded around $\epsilon_0 = \epsilon_1 = \epsilon_2 = \epsilon_3 = 0$, the three series through terms of the second degree (omission of any term indicating zero coefficient) are

$$s^2 = 1 - \epsilon_0 + \epsilon_2 + \epsilon_0^2 - \epsilon_0\epsilon_2 - \epsilon_1^2 + \ldots \qquad (24)$$

$$s = 1 - \frac{1}{2}\epsilon_0 + \frac{1}{2}\epsilon_2 + \frac{3}{8}\epsilon_0^2 - \frac{1}{4}\epsilon_0\epsilon_2 - \frac{1}{2}\epsilon_1^2 - \frac{1}{8}\epsilon_2^2 + \ldots \qquad (25)$$

$$m = -\frac{3}{2}\epsilon_0 + \frac{1}{2}\epsilon_2 + \epsilon_3 + \frac{3}{4}\epsilon_0^2 - \frac{1}{2}\epsilon_1^2 - \frac{1}{4}\epsilon_2^2 - \frac{1}{2}\epsilon_3^2 + \ldots \tag{26}$$

The mean values are found by taking the sum of the expected values term by term, as given in (20). For s^2 the second-degree contributions add to zero, but this is not so for the other two. The means are

$$\text{Mean}(s^2) = 1 \tag{27}$$

$$\text{Mean}(s) = 1 - \frac{3\sigma_r^2\Delta}{64\sqrt{\pi}} \tag{28}$$

$$\text{Mean}(m) = \left(\frac{5\Delta}{32\sqrt{\pi}} - \frac{1}{2}\right)\sigma_r^2 \tag{29}$$

The variances are found by taking the expected values of the <u>squares of the sums</u> of the first-degree terms. Thus,

$$\text{Var}(s^2) = E[(-\epsilon_0 + \epsilon_2)^2] = E(\epsilon_0^2) - 2E(\epsilon_0\,\epsilon_2) + E(\epsilon_2^2) \tag{30}$$

Or,

$$\text{Var}(s^2) = \frac{3\sigma_r^2\Delta}{8\sqrt{\pi}} \tag{31}$$

Similarly,

$$\text{Var}(s) = E[(-\frac{1}{2}\epsilon_0 + \frac{1}{2}\epsilon_2)^2] \tag{32}$$

Or,

$$\text{Var}(s) = \frac{3\sigma_r^2\Delta}{32\sqrt{\pi}} \tag{33}$$

Again,

$$\text{Var}(m) = E[(-\frac{3}{2}\epsilon_0 + \frac{1}{2}\epsilon_2 + \epsilon_3)^2] \tag{34}$$

Or,

$$\mathrm{Var}(m) = \left(1 + \frac{27\Delta}{32\sqrt{\pi}}\right)\sigma_r^{\,2} \tag{35}$$

The foregoing formulas are the ones sought, but as an excercise in checking, the mean and variance of M are obtained. The expansion of M is

$$M = 1 - \frac{3}{2}\epsilon_0 + \frac{1}{2}\epsilon_2 + \epsilon_3 + \frac{15}{8}\epsilon_0^{\,2} - \frac{3}{4}\epsilon_0\epsilon_2$$

$$- \frac{3}{2}\epsilon_0\epsilon_3 - \frac{1}{2}\epsilon_1^{\,2} - \frac{1}{8}\epsilon_2^{\,2} + \frac{1}{2}\epsilon_2\epsilon_3 \tag{36}$$

$$\mathrm{Mean}(M) = 1 + \frac{37\sigma_r^{\,2}\Delta}{64\sqrt{\pi}} \tag{37}$$

$$\mathrm{Var}(M) = \left(1 + \frac{27\Delta}{32\sqrt{\pi}}\right)\sigma_r^{\,2} \tag{38}$$

The curious result that the variance of M seems to be the same as the variance of m calls for some further analysis. Although nothing in the derivations of means and variances depends on it, the distribution of m has been assumed to be normal. Now in general, if W is a nonnegative variable and w = logW is normally distributed, with mean b and standard deviation c, then the mean and variance of W are given by the equations

$$\mathrm{Mean}(W) = \exp(b + \tfrac{1}{2}c^2) \tag{39}$$

$$\mathrm{Var}(W) = [\exp(2b + c^2)]\,[\exp(c^2) - 1] \tag{40}$$

On expanding the exponentials to one term, and substituting the mean of m for b and the variance of m for c^2, the results are:

$$\text{Mean}(W) = 1 + \left(\frac{5\Delta}{32\sqrt{\pi}} - \frac{1}{2}\right) \sigma_r^2 + \frac{1}{2}\left(1 + \frac{27\Delta}{32\sqrt{\pi}}\right) \sigma_r^2 = 1 + \frac{37\sigma_r^2}{64\sqrt{\pi}} \tag{41}$$

$$\text{Var}(W) = [1 + \frac{37\sigma_r^2\Delta}{32\sqrt{\pi}}] \; [(1 + \frac{27\Delta}{32\sqrt{\pi}}) \; \sigma_r^2] \tag{42}$$

Accordingly, (37) agrees with (41), and to the first power of σ_r^2 (38) agrees with (42). This is as far as the formulas should be expected to agree, since the Taylor expansions have been taken only through terms of second degree.

7. Empirical Support for Hypothesized Distributions

The hypothesized normality of designated statistics was based primarily on general principles, and secondarily on empirical findings. On general principles, normality is assumed, because weighted averages of errors commonly tend to distribute themselves in approximately normal frequencies. In choosing between alternative statistics, as to which one would be taken as normal, the decision again was based on general principles. Thus s was chosen in preference to s^2 because its standard deviation is only half as large as that of s^2, and the smaller standard deviation leaves more room to spread symmetrically about the mean; or more generally, because the square-root of a nonnegative variate is typically more nearly normal than the original. Similarly, m was taken to be normal rather than M, because the logarithm of a nonnegative variate is typically more nearly normal than the original.

The parameters of the distributions were derived by a straightforward mathematical development from stated premises. They have been expressed in terms of mathematical constants and one physical parameter σ_r^2. Only σ_r^2 has to be estimated from data, in order to complete the specification of all distributions employed.

The theoretical distributions were subjected to an empirical test by computing a number of sample values of I_0, s, m using data from the Dry Gulch*[1] experiments. All of these statistics were calculated from runs on Arc 7. This arc had a radius of 0.53 miles (0.85 km) and angular separation of 2°, which corresponds to arc segments of 29.77 meters. The runs had been divided into three classes on the basis of stability, but only Category 2 had enough runs to furnish a broad range of values of σ_y. Out of 44 runs in Category 2, eight were chosen for analysis. Four runs (Nos. 69, 18, 77, 56) showing the lowest values of σ_y (43.9, 50.4, 58.1, 62.1 meters respectively), two runs (Nos. 49, 59) showing values of σ_y near the middle of the distribution (σ_y = 102.9 meters for both runs), and two runs (Nos. 3, 87) showing the highest values of σ_y (154.2, 165.4 meters respectively) were selected, so as to represent the range of experience in these runs. Run No. 87, showing the highest value of σ_y, proved to be markedly bimodal. This run was omitted in the estimation of σ_r^2 but was included in the tests of normality.

Using the full set of observations on each run, the usual concentration parameters were computed, and then the values of r at each observation post were estimated from the quotient of the observed concentration and the fitted Gaussian concentration. The sample values of r used for the estimation of σ_r^2 were taken from those observation posts included between the limits $-2.15\sigma_y \leq y - \bar{y} \leq 2.15\,\sigma_y$. There were 83 values in all; these are listed in ascending order in Table 5. The mean of r for these 83 values was 0.973 and the standard deviation (defined as the square-root of the unbiased estimate of variance) was 0.247.

For each of the eight runs an estimate of r_0 was made. To this end, the actual peak concentration a_0 was estimated by parabolic interpolation, using the observed maximum and one observation to either side. A parabola was fitted to these three points, and its calculated maximum was taken as a_0. The peak concentration on the fitted normal curve (value at $y = \bar{y}$) was taken as f_0, and

*Haugen, D. and J. Fuquay (Editors) 1963; The Ocean Breeze and Dry Gulch Diffusion Programs. Vol 1, AFCRL-63-791(1)

TABLE 5
SAMPLE VALUES OF r

N = 83 Mean = .973 Standard Deviation = .247

Rank	r	Rank	r	Rank	r
1	.270	29	.914	57	1.071
2	.341	30	.924	58	1.073
3	.494	31	.925	59	1.078
4	.524	32	.929	60	1.080
5	.542	33	.932	61	1.092
6	.603	34	.936	62	1.094
7	.644	35	.940	63	1.096
8	.663	36	.945	64	1.099
9	.676	37	.951	65	1.101
10	.678	38	.953	66	1.115
11	.709	39	.954	67	1.122
12	.712	40	.955	68	1.124
13	.739	41	.958	69	1.136
14	.756	42	.971	70	1.135
15	.786	43	.980	71	1.151
16	.788	44	.985	72	1.177
17	.824	45	.992	73	1.221
18	.829	46	.995	74	1.250
19	.831	47	.996	75	1.277
20	.877	48	1.002	76	1.289
21	.879	49	1.002	77	1.313
22	.879	50	1.005	78	1.322
23	.885	51	1.008	79	1.354
24	.887	52	1.024	80	1.383
25	.891	53	1.038	81	1.414
26	.892	54	1.039	82	1.600
27	.900	55	1.042	83	1.824
28	.901	56	1.062		

r_0 was estimated by the quotient: $r_0 = a_0/f_0$. Also, for each run it was determined what integral multiple of the regular grid spacing would be equivalent to twice the measured standard deviation. A compilation of general data on the eight runs is exhibited in Table 6. Listed in Table 6 are the standard deviation σ for the individual run, the total number N of recorded concentrations, the multiple n of grid spacing needed to make Δ approximately 2, the actual value of Δ, and the estimated r_0.

TABLE 6
DATA ON FULL SAMPLES FOR SELECTED RUNS AND MULTIPLES (n) OF GRID SPACING USED TO OBTAIN $\Delta \approx 2$

x = .53 miles   angular separation 2°   d = 29.77 meters

Run no.	σ	N	n	Δ	r_0
3	154.2	36	10	1.93	1.028
18	50.4	15	4	2.36	1.074
49	102.9	22	7	2.04	1.210
56	62.1	14	4	1.92	1.034
59	102.9	22	7	2.04	0.974
69	43.9	15	3	2.03	1.041
77	58.1	17	4	2.05	1.240
87*	165.4	30	11	1.98	1.185

*Markedly bimodal.

The grid spacing designated by n in Table 6 was applied to each run, using as many separate trials as possible without using any observation more nor less than once. Thus every observation was included once and only once. The number of trials on each run, the number of observations on each trial, and the calculated values of I_0, s, m, M are presented in Table 7. In all, there were 50 trials.

TABLE 7
EMPIRICAL RESULTS WITH $\Delta \approx 2$
VALUES OF I_0, s, m, M

DRY GULCH ARC 7 CATEGORY 2

X = .53 miles Angular separation 2° d = 29.77 meters

Run	Trial	No. of obs.	I_0	s	m	M
3	1	4	.988	.973	.012	1.012
	2	3	1.101	1.022	-.047	.954
	3	3	1.054	1.030	.005	1.005
	4	3	1.014	.984	-.003	.997
	5	3	1.169	1.146	.007	1.007
	6	4	1.023	1.099	.099	1.104
	7	4	.925	.953	.057	1.059
	8	4	.942	.855	-.070	.932
	9	4	.850	.831	.004	1.004
3	10	4	.934	.919	.011	1.011
18	1	4	.950	.956	.078	1.081
	2	3	1.152	.811	-.280	.756
	3	4	.991	1.023	.103	1.109
18	4	4	.907	1.191	.344	1.410
49	1	3	1.083	.705	-.239	.787
	2	3	1.250	.959	-.075	.928
	3	3	1.246	1.119	.083	1.086
	4	3	.825	1.327	.666	1.945
	5	3	.895	1.245	.520	1.683
	6	4	.797	.701	.061	1.063
49	7	3	.904	.556	-.296	.744

TABLE 7 (continued)

Run	Trial	No. of obs.	I_0	s	m	M
56	1	3	.903	.890	.021	1.021
	2	3	1.088	.993	-.056	.946
	3	4	.922	1.101	.214	1.238
56	4	4	1.087	.963	-.086	.918
59	1	4	.866	.948	.064	1.066
	2	3	.908	.744	-.227	.797
	3	3	.910	.818	-.133	.875
	4	3	.972	.994	-.004	.996
	5	3	1.163	1.175	-.016	.984
	6	3	1.182	1.106	-.093	.911
59	7	3	.999	1.013	-.013	.987
69	1	5	.989	.907	-.046	.955
	2	5	1.042	.980	-.021	.979
69	3	5	.969	1.080	.148	1.159
77	1	5	.954	1.188	.435	1.544
	2	4	1.228	.839	-.166	.847
	3	4	.873	.855	.193	1.213
77	4	4	.944	1.081	.350	1.420
87*	1	3	.738	1.004	.478	1.612
	2	3	1.492	1.050	-.182	.834
	3	3	1.524	1.028	-.224	.799
	4	3	1.645	1.002	-.326	.722
	5	3	1.242	.995	-.052	.950
	6	3	1.015	.991	.146	1.157
	7	2	.879	.835	.118	1.125
	8	2	.867	.761	.039	1.040
	9	2	.637	.827	.432	1.540

*Markedly bimodal.

TABLE 7 (continued)

Run	Trial	No. of obs.	I_0	s	m	M
87*	10	3	.652	.758	.320	1.378
	11	3	.309	1.187	1.517	4.561

*Markedly bimodal.

Using $\Delta = 2$, $\sigma_r = .25$ in the formulas for the means and variances, the following calculated values of means and standard deviations were obtained.

Mean I_0 = 1.000	Std. Dev. I_0 = 0.188
Mean s = 0.997	Std. Dev. s = 0.081
Mean m = -0.020	Std. Dev. m = 0.349

It would have been perfectly feasible to plot the 50 empirical values of each statistic on normal probability paper, to check the distributions. An alternative method, actually used, is to compute the normal value that should correspond to any given rank, and then plot the empirical value at a given rank against the theoretical value at the same rank. Plots for I_0, s, and m are displayed, respectively, in Figs. 2, 3, and 4. Remembering that some of the statistics have been computed for a distinctly bimodal distribution, the general correspondence between actual and theoretical seems passably good.

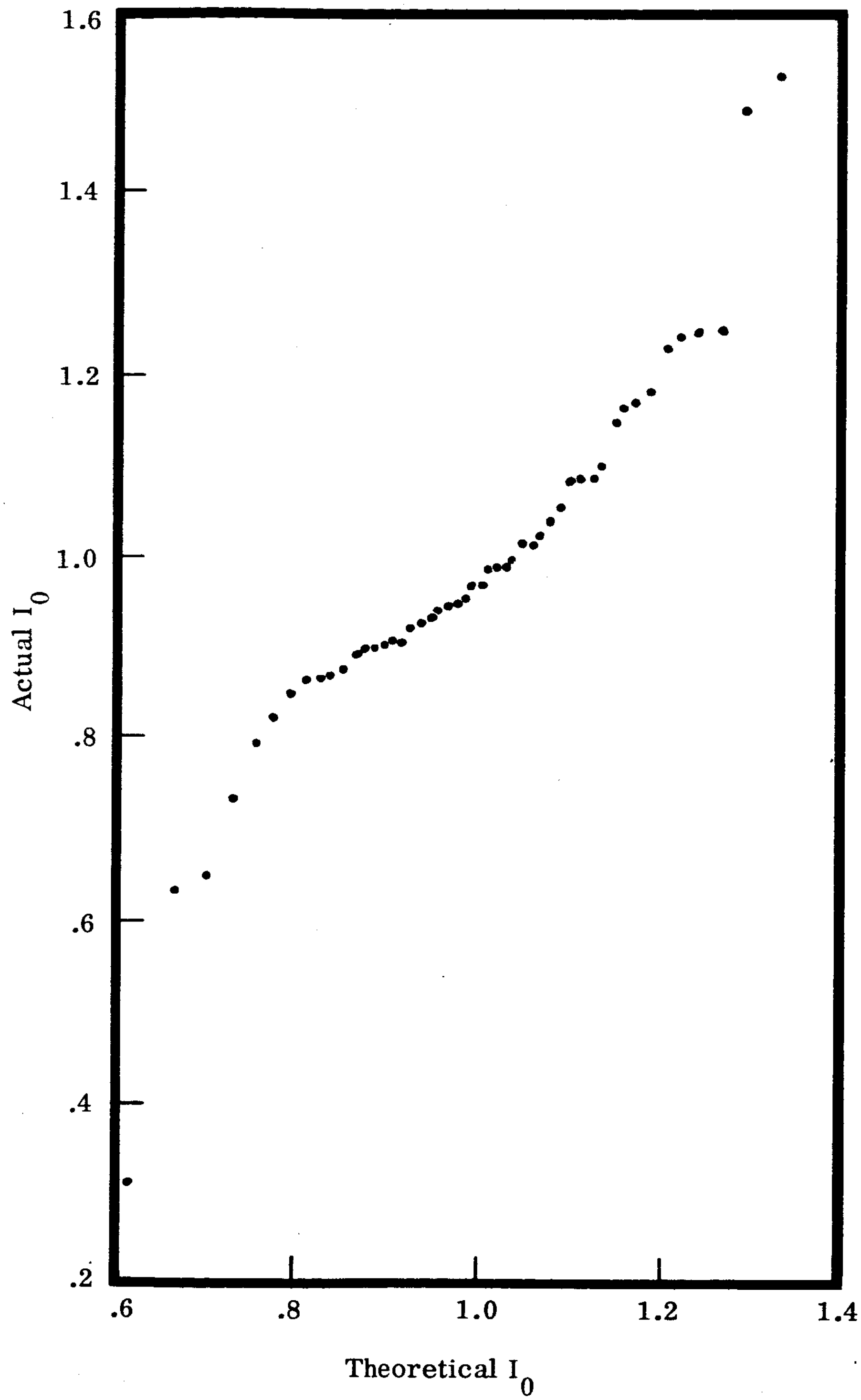

Fig. 2. Empirical test of normality of the distribution of I_0

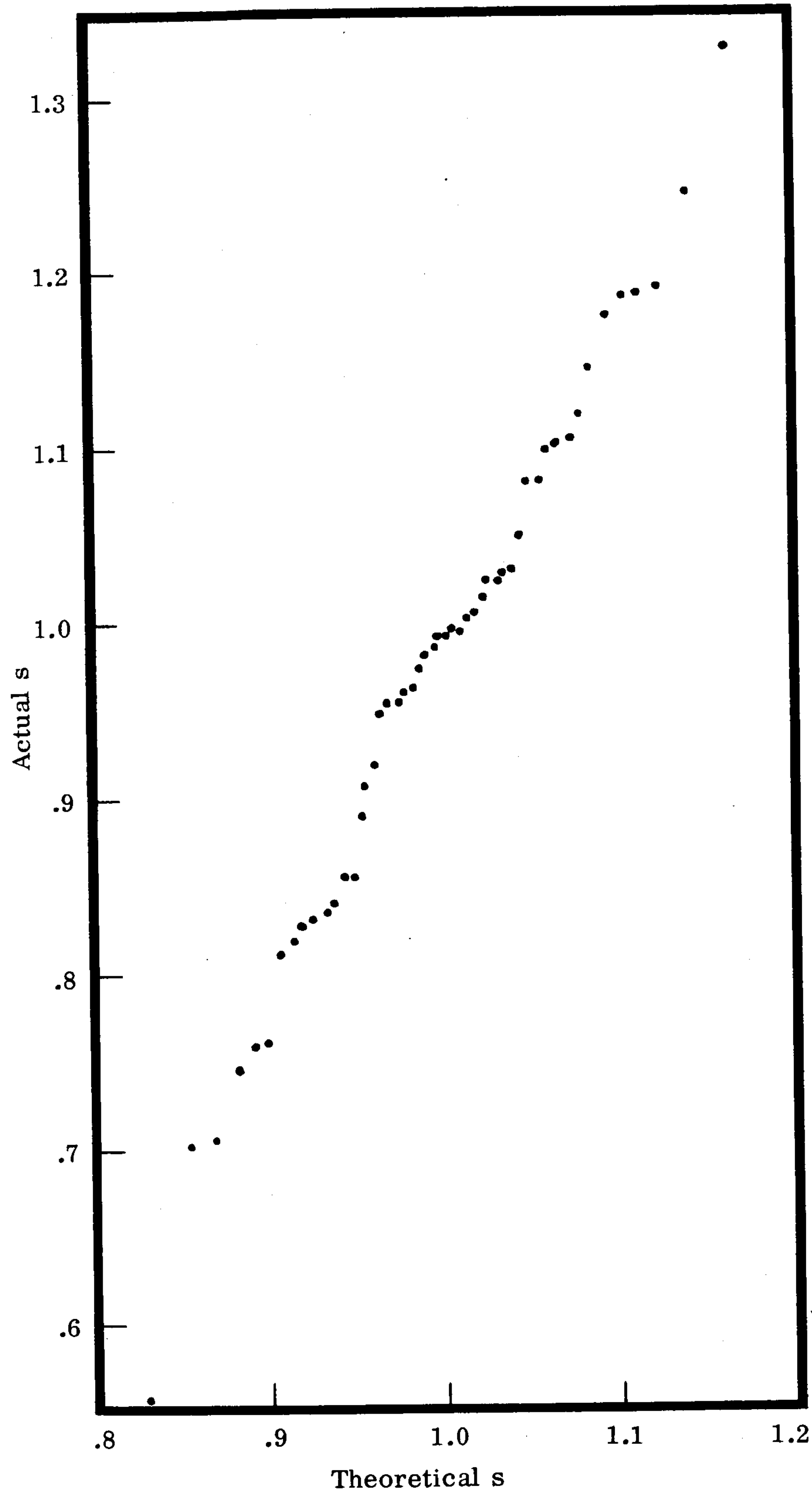

Fig. 3. Empirical test of normality of the distribution of s

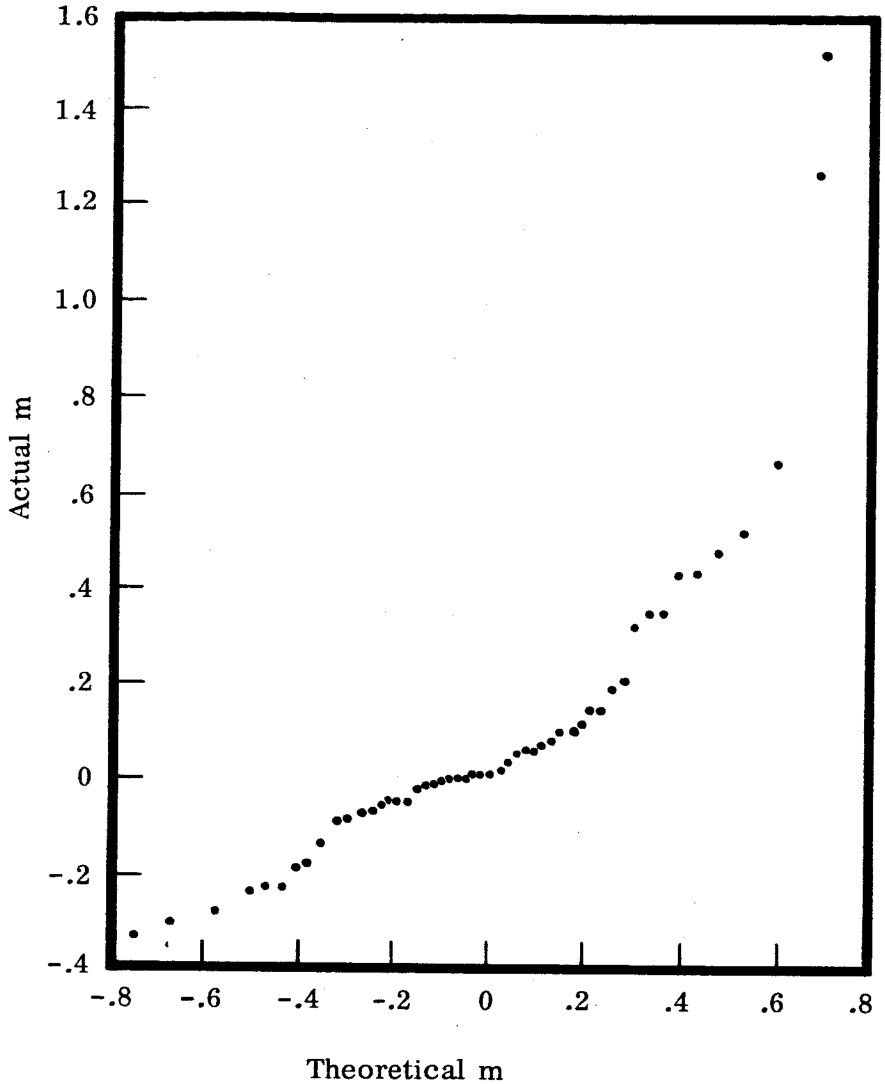

Fig. 4. Empirical test of normality of the distribution of m

APPENDIX B

APPENDIX B

IBM 1620 Fortran Program for Layered Diffusion Models

The mathematical model is described in the text. The program solves the diffusion equation for each point on a polar coordinate grid for a maximum of 16 radii and each angle in one quadrant. Values of ground concentration from each level are available as auxiliary print out while the final print is the total sum for the surface from all layers. A different centerline direction may be given for each layer and is properly accounted for by the program so long as the total difference between layers does not exceed 90 degrees of arc.

Control cards required; all except first are right adjusted.

1. Title card col 1-72 may contain any identifying remarks.
2. Format 8I4

col 1-4	LM - number of layers to be calculated, max is 6
col 5-8	NN - number of degrees either side of centerline for which values are to be computed, max is 45.
col 9-12	MDIR - average centerline direction for all layers.
col 13-16	MM - control that permits starting calculations at the source, MM = 0 or any given distance away from the source, e.g., if close in concentration are very low and the maximum is expected at about 10 km one can compute from 5-20 km by setting MM = 5.

3. Format 8I4 Wind directions in layers

col 1-4	Wind direction in degrees in layer 1
col 5-8	Wind direction in degrees in layer 2
col 21-24	Wind direction in degrees for layer 6

4. Format 8 F 9.0 Initial source horizontal σ cards

col 1-9 σ_1 for layer 1 (see text)

col 10-18 σ_2 for layer 2

col 19-27 σ_3 for layer 3

col 46-54 σ_6 for layer 6

5. Format 8 F 9.0 Initial source vertical σ cards

col 1-9 σ_1 for layer 1

col 10-18 σ_2 for layer 2

col 46-54 σ_6 for layer 6

NOTE: If Gaussian form for each layer is assumed, these will be calculated values like the horizontal σ. If these slices are to be used with integration for final concentration as done in this report $\sigma_i = 1.0$ for all layers.

6. Format 8 F 9.0 Height of each layer

col 1-9 Height of layer 1 (meters)

col 10-18 Height of layer 2

col 46-54 Height of layer 6

7. Format 8 F 9.0 Wind speed in each layer

col 1-9 Wind speed in layer 1 (m/s)

col 10-18 Wind speed in layer 2

col 46-54 Wind speed in layer 6

8. Format 8 F 9.0 Deposition factor

col 1-9 Deposition factor for layer 1

col 10-18 Deposition factor for layer 2

col 46-54 Deposition factor for layer 6

9. Format 8 F 9.0 σ_y a card

σ_y and σ_z are given in the form of a power law $\sigma_y = a\,x^b$.

Card No. 9 contains a coefficient for σ_y.

col 1-9 a coefficient for σ_y for layer 1

col 10-18 a coefficient for σ_y for layer 2

col 46-54 a coefficient for σ_y for layer 6

10. Format 8 F 9.0 σ_y b card

col 1-9 b coefficient for σ_y for layer 1

col 10-18 b coefficient for σ_y for layer 2

col 46-54 b coefficient for σ_y for layer 6

11. Format 8 F 9.0 σ_z a card

col 1-9 a coefficient for σ_z for layer 1

col 10-18 a coefficient for σ_z for layer 2

col 46-54 a coefficient for σ_z for layer 6

12. Format 8 F 9.0 σ_z b card

col 1-9 b coefficient for σ_z for layer 1

col 46-54 b coefficient for σ_z for layer 6

13. Format 6 E 10.0 Q card - source strength for each layer in floating exponent format, may be percent of total if calculating χ/Q

col 1-10 Q for layer 1

col 11-20 Q for layer 2

col 51-60 Q for layer 6

14. Format 2 F 9.0 Radii and layer thickness control

col 1-9 Radii control, if one km spacing is required this number is 1., if one meter spacing is required this number is .01, if two km spacing is required this number is 2., etc.

col 10-18 Thickness control, for vertical Gaussian distributions this number is 2., for integrated model this is the layer thickness.

15. Format I 4 Blank card is last case, 1 punch is col 4 indicates another case to follow and computer will proceed.

Output is punched cards.

Sense switch 3 controls intermediate output. If surface concentration contributions from each layer are desired, Switch 3 should be on, if only the total surface concentration from all layers are required, it should be off. In the on position, it increases running time up to 2 minutes per layer.

Running time is approximately 5 minutes per layer plus 12 minutes for input/output and initialization procedures.

There are two pause instructions, the first is after completion of peak concentration calculations so punched output can be removed from hopper. Press start and average concentration values will be punched. If card 15 is blank, the second pause is executed, and the program ended or more input cards may be read into the machine, and the program restarts when the start button is pushed.

A 40K memory is required for this program with card input/output. Progress reports are printed on the console typewriter each time a layer calculation is begun.

```
*0404
C       INSTANTANEOUS POINT SOURCE LAYERED DIFFUSION PROGRAM
C   PERMITS INPUT OF 6 LAYERS OF SOURCE AND DIFFUSION PARAMETERS
        DIMENSION TITLE(36),NTHETA(6),HT(6),VD(6),UBAR(6),SIGY(6,16)
        DIMENSION SIGZ(6,16),SIG1(6),SIG2(6),E(6),F(6),G(6),H(6),R(16)
        DIMENSION A(6,16),D(6,16),C(6,16),    X(16),XDQ(91,16),XYL(6),Q(6)
        DIMENSION XZL(6),XY(6),XZ(6),SZ2(6,16),SYZ(6,16),SIGYR(6,16)
        COMMON SIGY,SIGZ,SIGYR,SZ2,SYZ,XDQ,A,C,D,X,R
  300   FORMAT (36A2)
  301   FORMAT (8I4)
  302   FORMAT (8F9.0)
  303   FORMAT (6E10.0)
  310   FORMAT (6E10.3/6E10.3/6E10.3)
  350   FORMAT (36A2//8H AZIMUTH,10X,5H X AT,2X,F4.0,36H  KM   INCREMENTS
       1FROM RELEASE POINT/8H DEG LYR,10X7H1ST R =,I4)
  351   FORMAT (2I4,6E10.3/(8X,6E10.3/8X,6E10.3)/)
  352   FORMAT (25X,22H AVERAGE CONCENTRATION)
  360   FORMAT (11HBEGIN LAYER,I4)
  100   READ 300,(TITLE(I),I=1,36)
        READ 301,LM,NN,MDIR,MM
        READ 301,(NTHETA(I),I=1,LM)
        READ 302,(SIG1(I),I=1,LM)
        READ 302,(SIG2(I),I=1,LM)
        READ 302,(HT(I),I=1,LM)
        READ 302,(UBAR(I),I=1,LM)
        READ 302,(VD(I),I=1,LM)
        READ 302,(E(I),I=1,LM)
        READ 302,(F(I),I=1,LM)
        READ 302,(G(I),I=1,LM)
        READ 302,(H(I),I=1,LM)
        READ 303,(Q(I),I=1,LM)
        READ 302,FM,DZ
        PUNCH 350,(TITLE(I),I=1,36),FM,MM
        DO 110 I=1,91
        DO 110 J=1,16
        X(J)=0.
  110   XDQ(I,J)=0.
        DO 120 J=1,6
        XYL(J)=0.
        XZL(J)=0.
        XY(J)=0.
  120   XZ(J)=0.
        AM=MM
        DO 130 J=1,LM
        XYL(J)=(LOGF(SIG1(J))-LOGF(E(J)))/F(J)
        XZL(J)=(LOGF(SIG2(J))-LOGF(G(J)))/H(J)
        XY(J)= EXPF(XYL(J))+(AM*(1000.*FM))
        XZ(J)= EXPF(XZL(J))+(AM*(1000.*FM))
        DO 130 I=1,16
        SIGY(J,I)=(XY(J)**F(J))*E(J)
        SIGZ(J,I)=(XZ(J)**H(J))*G(J)
        XY(J)=XY(J)+(1000.*FM)
        XZ(J)=XZ(J)+(1000.*FM)
  130   CONTINUE
        DO 190 J=1,LM
        DO 190 I=1,16
        SZ2(J,I)= SIGZ(J,I)* SIGZ(J,I)
        SYZ(J,I)= SIGZ(J,I)* SIGY(J,I)
        AI=I+MM
        R(I)=((AI-1.)*(1000.*FM))+1.
        SIGYR(J,I)=SIGY(J,I)/R(I)
```

```
190   C(J,I)=.0001523/(SIGYR(J,I)*SIGYR(J,I))
200   DO 210 J=1,LM
      AA=VD(J)/UBAR(J)
      BB=HT(J)*HT(J)/2.
      DD=7.874
      DO 210 I=1,16
      A(J,I)=AA*R(I)+BB/SZ2(J,I)
210   D(J,I)=DD*SYZ(J,I)*SIGY(J,I)
      DO 275 I=1,LM
      PRINT 360,I
      L=NTHETA(I)-MDIR+46
      DO 250 K=1,16
      X(K)=Q(I)*(EXPF(-A(I,K)))/D(I,K)
250   XDQ(L,K)=XDQ(L,K)+X(K)
      IF(SENSE SWITCH 3) 251,252
251   PUNCH 351,NTHETA(I),I,(X(K),K=1,16)
252   DO 275 J=1,NN
      CC=J*J
      DO 255 K=1,16
255   X(K)=Q(I)*(EXPF(-A(I,K)-C(I,K)*CC))/D(I,K)
      LL=NTHETA(I)-J
      IF (MDIR-45-LL) 260,260,265
260   L=LL-MDIR+46
      DO 263 K=1,16
263   XDQ(L,K)=X(K)+XDQ(L,K)
      IF (SENSE SWITCH 3) 264,265
264   PUNCH 351,LL,I,(X(K),K=1,16)
265   LL=NTHETA(I)+J
      IF(MDIR+45-LL) 275,270,270
270   L=LL-MDIR+46
      DO 273 K=1,16
273   XDQ(L,K)=X(K)+XDQ(L,K)
275   CONTINUE
      LL=MDIR-46
      N=0
      DO 284 I=1,91
      L=LL+I
      DO 283 J=1,16
283   XDQ(I,J)=DZ/2.*XDQ(I,J)
      PUNCH 351,L,N,(XDQ(I,K),K=1,16)
      DO 284 K=1,16
284   XDQ(I,K)=XDQ(I,K)/2.39
400   PAUSE
      PUNCH 352
      PUNCH 350,(TITLE(I),I=1,36),FM,MM
      DO 285 I=1,91
      L=LL+I
285   PUNCH 351,L,N,(XDQ(I,K),K=1,16)
      READ 301,NXTCSE
      IF (NXTCSE) 100,500,100
500   PAUSE
      GO TO 100
      END
```